Decentralized Air Traffic Control in a High Density Corridor Subject to Separation Control Non-uniformity

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The characteristics of decentralized air traffic control in a high-density corridor subject to separation control non-uniformity are discussed. A high-density corridor is expected to be a one-way air traffic route where only aircraft equipped with airborne surveillance systems are allowed to fly in order to achieve airborne self separation. The air traffic behavior in a high-density corridor under a decentralized control strategy that achieves safe and efficient operation of the air traffic flow with the maximum traffic volume is investigated through numerical simulations. Each simulation result is evaluated in terms of safety and workload. The numerical simulations reveal that some non-uniformity in the aircraft control parameters cause severe conflict situations. It is also found that the aircraft behave collaboratively for the conflict resolution when the uniform distance to begin separation control and the uniform maneuver swiftness are applied. It is concluded that such collaborative separation control is the key to safe operation.

Key Words: Air Traffic Management, Traffic Flow, Airborne Surveillance, Decentralized Control

Nomenclature

\( a \): acceleration in flight direction, \( \text{m/s}^2 \)
\( d_{ij} \): distance between aircraft \( i \) and \( j \), \( \text{m} \)
\( d^* \): separation control distance, \( \text{m} \)
\( g \): Earth gravity acceleration, \( \text{m/s}^2 \)
\( x \): aircraft longitudinal position, \( \text{m} \)
\( y \): aircraft lateral position, \( \text{m} \)
\( y_a \): lateral position of allocated route, \( \text{m} \)
\( \alpha, \beta \): separation control parameter
\( \phi \): bank angle, rad
\( \psi \): azimuth angle, rad
\( \psi_a \): azimuth angle for conflict avoidance, rad
\( \psi_r \): azimuth angle for route following, rad
\( \psi_t \): target azimuth angle, rad

Subscript

\( i, j \): aircraft number

1. Introduction

The current oceanic routes and the cruising routes between congested airports have high-density traffic, where many aircraft form a one-way high-density traffic flow. Recently, there have been plans to introduce an air corridor to increase the traffic capacity and decrease the air traffic controllers’ workload.1,2) In the air corridor, aircraft will be required to be equipped with airborne surveillance systems3) and allowed to make the airborne separation control without air traffic controllers’ instructions. Several studies have been carried out on the high-density air corridor mainly concerning its design4) and preliminary operation procedures.5) However, no simulation studies had been carried out to investigate a practical operation procedures and its feasibility prior to the authors’ studies.6,7)

The airborne separation in such air corridors seems similar to the airborne in-trail separation in arrival routes8–11) at a glance. However, the in-trail separation control aims to achieve a constant interval by leading all aircraft to have the same flight speed. In contrast, the airborne separation control in the air corridor should lead all aircraft to maintain each one’s optimum flight speed while keeping sufficient separation. The authors, therefore, have sought an appropriate control algorithm for the high-density air corridor. From trial-and-error studies, practical maximum capacity and corresponding procedures can be determined. In this case, the maximum traffic capacity is determined by the initially assumed procedure. In contrast, the authors consider that it is also possible to obtain the maximum traffic capacity determined by the aircraft dynamics and navigation performance, and that this traffic capacity becomes larger than the one obtained by the procedure-based study. Therefore, the authors have carried out the air corridor procedure studies to clarify a decentralized control capable of the maximum traffic volume with sufficient safety and efficiency.6) An appropriate route structure for the safe treatment of an air corridor with the flight speed distribution has also been proposed.7) In addition to the flight speed distribution, it is also expected that the swiftness of the conflict avoidance maneuver and the condition to begin it will have some distribution due to the aircraft types, weight and other factors, in the actual air traffic. In this study, therefore, the control parameter distribution is newly introduced, and its influence on the traffic behavior is investigated through numerical simulations.
2. Air Traffic Flow Model

2.1. Aircraft model
The aircraft is modeled as a mass particle, and only its level motion is considered. The coordinates are shown in Fig. 1. The x and y axes are defined along the flight direction and right hand to it. The aircraft equations of motion are given as follows:

\[
\begin{align*}
\dot{x}_i &= v_i \cos \psi_i \\
\dot{y}_i &= v_i \sin \psi_i \\
\dot{\psi}_i &= \frac{g}{v_i} \tan \varphi_i 
\end{align*}
\]

where \(\varphi_i\) is the lateral displacement of the \(i\)th aircraft from its allocated route, and \(\psi_i\) is determined according to the difference between the azimuth angle \(\psi_i\) to lead the aircraft and \(\psi_j\) to the target one \(\Psi_f\).

The authors have proposed a route structure that has sub-routes with flight speed allocation to cope with the flight speed distribution in a high-density air corridor. This route model has some sub-routes within a certain range around the optimum route. Each sub-route has its allocated speed range, and each aircraft is required to fly on a sub-route corresponding to its flight speed. In this paper, the five sub-routes model shown in Fig. 3 is considered. It is considered that the maximum traffic capacity would be achieved when the aircraft compose a traffic flow with the same distance as the separation control distance as shown in Fig. 4. This traffic flow is defined as the one with the maximum traffic capacity in this paper. In the following sections of this paper, we aim to clarify the separation control strategy that is able to achieve a safe and efficient operation of an air corridor with the same traffic volume as the maximum traffic capacity.

2.3. Air traffic model
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\[
\begin{align*}
\Psi_i &= \alpha[\Psi_i - \psi_i] \\
\Psi_i &= \Psi_l(\Delta y_i) + \sum_j \psi_a(d_{ij}) 
\end{align*}
\]

\(\Delta y_i\) is the lateral displacement of the \(i\)th aircraft from its allocated sub-route: \(\Delta y_i = y_i - y_i^0\), where \(y_i^0\) is the \(y\) position of the sub-route that \(i\)th aircraft is allocated. The bank angle \(\psi_i\) is determined according to the difference between the azimuth angle \(\psi_i\) and the target one \(\Psi_f\). The target azimuth angle \(\psi_i\) is defined as the sum of the azimuth angle \(\psi_i\) and \(\psi_{a_i}\), where \(\psi_i\) is the azimuth angle to lead the aircraft to its allocated route, and \(\psi_{a_i}\) is the one to achieve the separation control. These functions are defined as follows:

\[
\psi_l(\Delta y_i) = -\beta_r(y_i - y_i^0)
\]

\[
\psi_a(d_{ij}) = \begin{cases} 
0 & d_{ij} > d^f \\
\beta_r(d^f - d_{ij}) & d_{ij} < d^f \text{ and } y_i > y_j \\
-\beta_r(d^f - d_{ij}) & d_{ij} < d^f \text{ and } y_i < y_j 
\end{cases}
\]
3. Numerical Analyses

3.1. Parameters and assumptions

In the numerical simulations, the separation minima and the separation control distance are set to 10 NM (≈ 18,520 m) and 10.5 NM (≈ 19,446 m), respectively. The air traffic flow is composed of 20 aircraft. The aircraft are placed along the x-axis with intervals equal to the separation control distance, and placed randomly along the y-axis for the initial condition as shown in Fig. 5. The analysis range is fixed, and the front of this range is considered to link to the end to simulate an infinite length traffic flow. When an aircraft’s separation control distance exceeds the front of the analysis range, the aircraft takes into account the aircraft around the end of the analysis range for its separation control, and vice versa. The flight speed of each aircraft is given randomly according to the uniform distribution between 230 and 250 m/s. The route width is given as three times that of the separation control distance. The analysis range and the route width are also shown in Fig. 5. In this figure, the circles surrounding each aircraft denote the separation minima domain, and the arrows denote the flight speed and direction, where the aircraft azimuth angles are exaggerated three times. The colors of the minimum separation circles also show the aircraft flight speed according to the color bar. The following flight speed allocation is applied to each sub-route: (i) 230–234 m/s, (ii) 234–238 m/s, (iii) 238–242 m/s, (iv) 242–246 m/s and (v) 246–250 m/s. The air traffic behavior converges to some steady state as the simulation time progresses. To focus on the traffic behavior difference due to the separation control strategy, long-term simulations are carried out for 100,000 s. Table 1 shows the standard set of the simulation parameters. \( \psi_i(\Delta y_i) \) has a limitation between \(-0.087\) rad (\(= -5\) deg) and \(0.087\) rad (\(= 5\) deg), and no limitation is applied for \( \psi_f(\Delta y_f) \) and \( \psi_l \). Each case of numerical simulations is carried out using 50 sets of initial conditions, and the average values of the evaluation indices are examined.

3.2. Evaluation indices

The following indices are applied for evaluation: air traffic safety and pilots’ workload. All aircraft are required to have distances larger than the separation minima to avoid conflict, and it is also more desirable that the distances are larger than the separation control distance. To evaluate the safety, \( d_{i,j}^{\text{conf}} \) and \( d_{i,j}^{\text{ctrl}} \) are introduced as the following equations

\[
\begin{align*}
    d_{i,j}^{\text{conf}} &= \left\{ \begin{array}{ll}
        10 \text{ NM} - d_{i,j} & (d_{i,j} < 10 \text{ NM}) \\
        0 & (d_{i,j} \geq 10 \text{ NM})
    \end{array} \right. \\
    d_{i,j}^{\text{ctrl}} &= \left\{ \begin{array}{ll}
        10.5 \text{ NM} - d_{i,j} & (d_{i,j} < 10.5 \text{ NM}) \\
        0 & (d_{i,j} \geq 10.5 \text{ NM})
    \end{array} \right.
\end{align*}
\]

(9)

The evaluation indices accounting for safety \( E_{\text{conf}} \) and \( E_{\text{ctrl}} \) are introduced as follows

\[
\begin{align*}
    E_{\text{conf}} &= \frac{1}{N} \sum_{i,j} \int_{t} d_{i,j}^{\text{conf}} \, dt \quad (i < j) \\
    E_{\text{ctrl}} &= \frac{1}{N} \sum_{i,j} \int_{t} d_{i,j}^{\text{ctrl}} \, dt \quad (i < j)
\end{align*}
\]

(10)

where \( N \) is the number of aircraft. \( E_{\text{conf}} \) and \( E_{\text{ctrl}} \) are defined as the average of the time integration of the aircraft distances below the separation minima and the separation control distance, respectively. Since the conflict between aircraft must be avoided for safety assurance, \( E_{\text{conf}} = 0 \) are mandatory throughout numerical simulations. In addition, it is desirable that \( E_{\text{ctrl}} \) has a smaller value to minimize the conflict possibility. It is also desirable for the feasibility of the separation control strategy that the pilots’ workload is as small as possible. In this paper the workload is considered proportional to the amount of the azimuth angle change, and the index \( E_{\text{work}} \) is defined as follows

\[
E_{\text{work}} = \frac{1}{N} \sum_{i} \int_{t} |\psi_i| \, dt
\]

(11)

The evaluation indices are not computed for the first 20,000 s because the strong impact of initial condition for the indices was observed during this interval.

3.3. Numerical simulation and evaluation

3.3.1. Standard simulation result

The example illustration of the numerical simulation result using the initial condition shown in Fig. 5 and the standard parameters shown in Table 1 is presented in Fig. 6, where the aircraft positions, velocity and azimuth angles are depicted every 25,000 s. The yellow shadow indicates that the distance between the shadowed aircraft and one of its surrounding aircraft is below its separation control distance. If the distance between aircraft becomes smaller than the separation minima, the aircraft will be depicted with red shadow. According to the authors’ previous study, conflict often occurs when a pair of aircraft in the flight direction has a large flight speed difference in a congested area. In such a case, the faster aircraft in the rear of the slower one makes a swift lateral movement to overtake the slower one. This often results in conflict between the aircraft in the lateral position. The sub-route structure with the flight speed gradient leads the aircraft that have similar flight speed to fly on the same sub-route. This results in some aircraft flying in groups as those denoted by circles in Fig. 6. This enables the aircraft to avoid overtaking with a large
Fig. 5. Initial condition and analysis range.

Fig. 6. Typical traffic flow behavior, standard case.

Fig. 8. Typical conflict situation, random case.

Fig. 10. Typical conflict situation, random separation control distance case.
speed difference, and no conflict occurs throughout the set of simulations.

3.3.2. Separation control parameters

There are three parameters used in the separation control: $\alpha$, $\beta_r$, and $\beta_a$. The effects of these parameter values and their non-uniformity on the traffic flow behavior are examined. Many sets of numerical simulations are carried out changing each of these parameters between the following ranges: $\alpha = 0.5$–1.5, $\beta_r = 0.5$–1.5 $\times 10^{-6}$ and $\beta_a = 0.5$–1.5 $\times 10^{-3}$. In addition, the simulations where each parameter is given randomly according to the uniform distribution in the same range are also carried out. The other parameters are the same as those shown in Table 1.

The evaluation result is summarized in Fig. 7. In the figure, the standard case results are denoted as std, and other results are denoted by the coefficient part of the changed parameters: e.g., the $\beta_r = 1.25 \times 10^{-6}$ case is denoted by $\beta_r = \text{rand}$, the random $\beta_r$ case is denoted by $\beta_r = \text{rand}$ and so forth. This result shows that each parameter has optimality in safety $E_{\text{ctrl}}$ and workload $E_{\text{work}}$. It is also clarified that conflict rarely occurs throughout the simulations except for the cases applying the random parameters for $\alpha$ and $\beta_a$. When the parameters are given randomly, it is considered that the separation control behavior differences between aircraft become larger than those in the standard case, and this causes many conflicts. A typical conflict situation is shown in Fig. 8. A pair of aircraft with a large flight speed difference is the trigger of the conflict. In Fig. 8(a), aircraft (B) is about to overtake aircraft (A). The control parameters $\alpha$ of aircraft (A) and (B) are larger and smaller than its average respectively in this case, and aircraft (A) makes a swift turn to avoid conflict as shown in Fig. 8(b). In addition, in Fig. 8(c), parameter $\alpha$ of aircraft (C) is also smaller than average, and aircraft (C) makes only a slow turn. This results in a conflict between aircraft (A) and (C).

The separation control parameter difference results in the swiftness difference of the conflict avoidance maneuver. This leads the aircraft with the larger control parameter to make a larger effort to resolve conflict, and vice versa. In contrast, in the standard case, both aircraft equally share the effort for conflict resolution. The uniform control parameter is considered mandatory to achieve collaborative conflict avoidance, which results in safe operation.

3.3.3. Separation control distance

The separation control distance is also one of the parameters that determines the traffic flow behavior. Its influence has been investigated through the following cases of numerical simulations: the same separation control distance are given to all aircraft changing from 10.5 to 12.5 NM, and
the separation control distance are randomly given to each aircraft following the uniform distribution between 10.5 and 12.5 NM. Fifty cases of the simulations have been carried out using the same initial conditions as those in the previous sections.

The evaluation indices are shown in Fig. 9. This result shows that the separation control distance has its optimal value, and that the conflict occurs only in the random separation control distance case. The typical conflict situation is shown in Fig. 10. A pair of aircraft with a large speed difference in overtaking is also the conflict trigger in this case. In Fig. 10(a), aircraft (B) is overtaking (A), and aircraft (A) has a larger separation control distance than that of (B). Therefore only aircraft (A) begins turning to avoid conflict. In addition, because aircraft (B) does not make any maneuver, aircraft (A) makes a larger conflict maneuver than the standard case as shown in Fig. 10(b). In this case, aircraft (C) and (D) are unable to make sufficiently swift turn to avoid conflict with aircraft (A) as shown in Fig. 10(c).

When a pair of aircraft have a difference in their separation control distances, only the aircraft with the larger one makes the conflict avoidance maneuver. In this case, the conflict avoidance maneuver becomes approximately twice as large as the one in the standard case because the aircraft with the smaller separation control distance does not make any maneuver. It is considered, therefore, that even a small difference of separation control distance can result in conflict. In the standard case, the uniform separation control distance leads the aircraft to equally share the effort for conflict avoidance in the same way as the uniform control parameter case. This prevents excessive maneuvering to achieve safe operation.

4. Conclusion

The fundamental behavior of the decentralized air traffic flow control in a high-density corridor was investigated through numerical simulations. The investigations on the separation control parameters and the separation control distance clarified that it is indispensable for operation safety to apply the uniform control parameters to all aircraft to achieve collaborative conflict avoidance maneuvers. From these results, it is concluded that such collaborative separation control strategies are the key to operation safety and efficiency.

From the control parameter study, it was suggested that aircraft with similar control parameters behave with similar swiftness. Such similar aircraft behaviors are considered suitable for safe operation. Therefore, it is expected that some traffic rules to treat aircraft with similar flight performance as a group will achieve a more sophisticated traffic flow in a high-density corridor. There are many future works required to bring the self-separated high-density corridor into practical use (e.g., relative velocity information application, three-dimensional maneuver for conflict avoidance and dynamic configuration change of corridors). In addition, detailed investigations on emergency procedures are also indispensable. It is also an important subject to find simplified separation control strategies so that human pilots are actually able to make appropriate maneuvers for conflict avoidance. The evaluation indices must also be improved so that they can evaluate the air corridor procedure from a more practical viewpoint. The indices used in this study are sufficient to verify the conflict occurrence and to simply compare the workload amount in the fundamental simulations. However, more sophisticated evaluation indices are considered necessary to investigate an air corridor procedure worthy of practical use.

References