Chinese Journal of Aeronautics, (2014),**27**(1): 124–135

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Collision risk-capacity tradeoff analysis of an en-route corridor model

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Received 25 April 2013; revised 24 July 2013; accepted 16 September 2013
Available online 18 December 2013

KEYWORDS

Air traffic control;
Corridor;
Risk-capacity tradeoff;
Self-separation;
Simulation

Abstract Flow corridors are a new class of trajectory-based airspace which derives from the next generation air transportation system concept of operations. Reducing the airspace complexity and increasing the capacity are the main purposes of the en-route corridor. This paper analyzes the collision risk-capacity tradeoff using a combined discrete–continuous simulation method. A basic two-dimensional en-route flow corridor with performance rules is designed as the operational environment. A second-order system is established by combining the point mass model and the proportional derivative controller together to simulate the self-separation operations of the aircrafts in the corridor and the operation performance parameters from the User Manual for the Base of Aircraft Data are used in this research in order to improve the reliability. Simulation results indicate that the aircrafts can self-separate from each other efficiently by adjusting their velocities, and rationally setting the values of some variables can improve the rate and stability of the corridor with low risks of loss of separation.

1. Introduction

A corridor is defined as a long "tube" of airspace, in which groups of flights fly along the same path in one direction and accept responsibility for separation from each other. Multiple (parallel) lanes, self-separation, and dynamic activation rules are three of the prominent attributes of corridors. A well-designed corridor may reduce the airspace complexity, increase the airspace capacity, and decrease the workload of air traffic controllers.[1]

Previous research has looked at the initial design concept, optimal placement of corridors, and the topology of the network. John et al.[2] initially proposed and evaluated the conception of dynamic airspace super sectors (DASS), which is thought of as a network of one-directional, high-density highways in the sky. Safety, performance, and cost are three primary criteria used to measure design alternatives. Yousefi et al.[3] conducted a statistical analysis of city-pair traffic and

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

1000-9361
http://dx.doi.org/10.1016/j.cja.2013.12.007

the placement of a network of high-volume tube-shape sectors (HTS). Velocity vectors for small volumes of airspace were calculated and vector fields of the fluid velocity were created. After the analysis of the vector fields' topology, the geometries and locations of potential corridors were determined. Sridhar et al.[4] grouped airports into regions, and modeled a series of tubes connecting major regions. A network connecting the top 18 regions was designed, and the top 250 busy airports with the appropriate regions were associated by clustering techniques. Hoffman et al.[5] constructed a tube network and made an estimate of capacity-enhancing effects of tubes for airspace. A comprehensive list of design issues and some potential alternatives were created to enhance the tube design and tradeoffs. Xue et al.[6,7] studied the complexity of traffic in a selected corridor using simulation. A space–time map was developed to examine and visualize the utilization of corridors, suggest the number of lanes, and show the possibility of deploying corridors dynamically. Yousefi et al.[8,9] developed an initial operational procedure to implement flow corridor operations, and proposed a flow-based modeling approach to cluster 4DTs into potential corridors. A sliding time window was implemented to dynamically create and optimize a corridor's coordinates based on the changes in preferred trajectories.

The objective of this research is to develop models and methods for constructing collision risk-capacity tradeoff curves in a corridor.

2. Model description

2.1. Structure and assumptions of corridor

A two-dimensional en-route flow corridor is presented to be a tube of parallel high-altitude Q-routes structure which is assumed to be 80 nm (nautical mile) long and 16 nm wide with the route centerlines 8 nm apart and located at the FL350 as shown in Fig. 1.

Aircraft usually travel in the same direction from left to right by self-separation in the corridor. An aircraft may adjust its velocity and separation with the leading one, switch lanes for overtaking, or in extreme cases exit the corridor along paths that are at a divergence angle by 30° before the exit. Detailed movements of each aircraft are assumed as follows:

(1) All aircraft initially enter the corridor with random types, velocities, and separations with their leading ones.
(2) Each aircraft is under conditions of level fight that flies along the middle line of each corridor and self-separates with the aircraft in front according to a self-separation model by adjusting its acceleration and velocity.
(3) Any time the velocity of an aircraft is higher than the average velocity of the leading one by a velocity threshold, it attempts to switch the lane.
(4) Any time an aircraft gets within the minimum separation of the aircraft in front (loss of separation), it switches its lane or breaks out.
(5) The first aircraft in each lane and the aircraft whose separation with its leading aircraft is larger than a threshold value, it flies towards the target velocity.

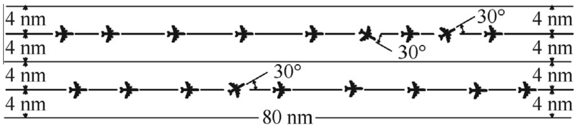

Fig. 1 Structure of corridor.

2.2. Aircraft performance model

2.2.1. Aircraft model

In this paper, the aircraft is modeled by using the point mass model (PMM). This model is adapted from the work of Glover and Lygeros.[10] Some key elements of the model are summarized here. The states of the model are the horizontal position x and y and the altitude z of the aircraft, the true airspeed v, the flight path angel γ, and the heading ψ. Table 1 illustrates the descriptions and primary dimensions of the state variables.

The control inputs to the model are the engine thrust T, the angle of attack ϕ, and the bank angle α. Table 2 outlines the descriptions and primary dimensions of the control variables.

The Newtonian dynamics equations of motion used in this paper are:

$$\begin{cases} \dot{x} = v\cos\psi\cos\gamma \\ \dot{v} = \dfrac{1}{m}(T\cos\alpha - D - mg\sin\gamma) \\ \dot{\psi} = \dfrac{1}{mv}(L + T\sin\alpha)\sin\phi \\ \dot{\gamma} = \dfrac{1}{mv}[(L + T\sin\alpha)\cos\phi - mg\cos\gamma] \end{cases} \tag{1}$$

where m is the mass of the aircraft and g is the gravitational acceleration. L and D denote respectively the lift and drag forces, which are functions of the state and the angle of attack as outlined as follows:

$$\begin{cases} L = \dfrac{C_L S\rho}{2}(1 + c\alpha)v^2 \\ D = \dfrac{C_D S\rho}{2}\left(1 + b_1\alpha + b_2\alpha^2\right)v^2 \end{cases} \tag{2}$$

where S is the surface area of the wings, ρ is the air density, and C_D, C_L, c, b_1, and b_2 are aerodynamic lift and drag coefficients whose values generally depend on the phase of the fight. During the cruising phase, all commercial airliners are usually assumed operating near trimmed flight conditions ($\gamma = \dot{\gamma} = 0$ and $\alpha \approx 0$), and then the lift is represented by:

Table 1 State variables.

Variables	Description	Primary dimension
x	Along-track position	Along-track
v	True airspeed	Along-track
y	Across-track position	Across-track
ψ	Heading	Across-track
z	Altitude	Vertical
γ	Flight-path angle	Vertical

Table 2 Control variables.

Variables	Description	Primary dimension
T	Thrust	Along-track
ϕ	Bank angle	Across-track
α	Angle of attack	Vertical