Empirical Exploration of Air Traffic Control Behaviour at Terminal Maneuvering Area: From an Air Traffic Flow Aspect

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Abstract: In a large-volume, high-density traffic background, air traffic manifests fluid-like microscopical characteristics. The characteristics are formed by the micro tailing actions between individual aircraft. Aircraft headway refers to the time interval between successive flying aircraft in air traffic flow, which is one of the most important characteristics of air traffic flow. The variation in aircraft headway reveals the air traffic control behaviour. In this paper, we study the characteristics of air traffic control behaviours by analyzing radar tracks in a terminal maneuvering area. The headway in arrival traffic flow is measured after the determination of aircraft trailing relationships. The headway evolutionary characteristics for different control decisions and the headway evolutionary characteristics in different phase-states are discussed, and some interesting findings are gotten. This work may be helpful for scholars and managers in understanding the intrinsic nature of air traffic flow and in the development of intelligent assistant decision systems for air traffic management.

Key words: air traffic; aircraft headway; traffic state; air traffic control

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0 Introduction

With the rapid development of the global air transportation industry, it is already difficult for airspace capacity to satisfy the ever-increasing traffic demand, causing air traffic congestion and the change of air traffic control behaviours[1]. The characteristics of air traffic control behaviours under different air traffic states are very useful to assess the airspace capacity, establish an air traffic flow model, and evaluate the efficiency of air traffic management operations.

Several methods focusing on air traffic flow states and air traffic controllers' behavior are developed. A series of traffic flow complexity metrics are developed in the last two decades. Classic metrics include static density[2], dynamic density[3], input-output[4], Lyapunov exponent of trajectory dynamics[5], and solution space-based metrics[6]. Dong et al.[7] found that the congestion segments presented the structural characteristics of unbalanced coverage and concentrated distribution to the crossing points. Liu et al.[8] used traffic situation graphics to illustrate the traffic flow situations in a single instant. Olive et al.[9] presented a new approach to separate air traffic trajectories. The trajectory clusters fostered good understanding of the traffic structure and of how controllers scheduled landings at Toulouse-Blagnac airport. Xiao et al.[10] presented a novel hybridized indirect and direct encoding (HybrID) genetic algorithm for solving air traffic network flow optimization problems. Yuan et al.[11] designed an identification method of traffic flow situation in terminal based on factor analysis and fuzzy clustering. Zhang et al.[12] found that notable phase transitions and hysteresis characteristic existed in the evolution

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process of the arrival traffic flow.

To understand the relationship between traffic flow complexity and air traffic controllers' workload, the weights of relevant indicators (e.g. traffic density, aircraft type mixture, potential conflict) are calibrated. The weight can be treated as the impact of each traffic scenario on the air traffic controllers' cognition. Monechi et al.[13] modelled a large-scale air transportation system as a complex, dynamic network of flights controlled by humans, and analyzed the probability distributions of delay time and potential conflict. Corver et al.[14] studied how trajectory uncertainties impacted controllers' workload with varying levels of traffic density and conflict intensity. Within the context of 4D trajectory operation, Zohrevandi et al.[15] designed several scenarios to measure how the level of 4D equipage affected controllers' workload in terminal and en-route sectors. As a summary of the literature review, existing studies seldom study the air traffic control behavior based on the characteristics of air traffic flow.

In a large-volume, high-density traffic background, air traffic manifests fluid-like microscopical characteristics. The characteristics are formed by the micro tailing actions between individual aircraft. Aircraft headway is a microcosmic parameter of traffic flow characterizing the aircraft tailing relationship. It describes the time interval between adjacent aircraft passing an observation point. At a microscopical level, the size of the aircraft headway is mainly affected by the traffic demand and the airspace capacity. When the demand is greater than the capacity, the aircraft headway is smaller; otherwise, it can be larger. At a microcosmic level, the aircraft headway depends on the air traffic controller's commands, and the controller adjusts aircraft separation by providing, for example, speed adjustment and maneuvering guidance. Therefore, aircraft headway characterizes the dynamic characteristics of the "human-in-the-loop" air traffic system. It can be used to understand the air traffic control behavior.

In this paper, the measurement of aircraft headway is established based on aircraft trajectories. And then the effects of the controller's behavior on air traffic flow and the headway variation characteristics under different air traffic flow states are discussed.

1 Data Extraction

In this paper, the measured flight trajectory data of the terminal maneuvering area (TMA) in Xiamen, China, are used. Fig. 1 presents a schematic diagram of the arrival and departure traffic flows.

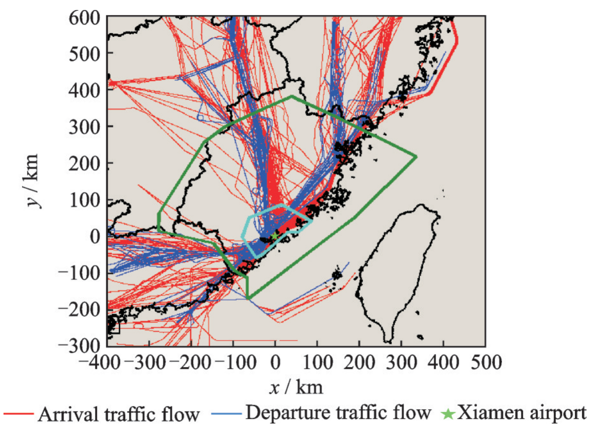

Fig.1 Arrival and departure traffic flows of Xiamen airspace

The aircraft headway reflects the headway evolution law between two successive aircraft with a trailing relationship. Since the arrival traffic flows converge from different directions and are affected by air traffic controller's command in terms of adjusting speed, adjusting altitude, orbiting or radar vectoring. It is very difficult for a trailing relationship between aircraft to exist for an extended period of time. Therefore, the following two issues need to be resolved: Determining the trailing relationship and measuring the headway.

(1) Determining the trailing relationship

Since the air traffic controller usually completes the approach sequence for arriving aircraft from all directions in the final approach fix (FAF), the landing order of the aircraft can be deemed as completely determined at the FAF, and the trailing relationships of the aircraft have been clarified. Although the trailing relationships of the aircraft continuously change throughout the arrival process, the landing order is determined from the aircraft's entry into the TMA. An aircraft in different air traffic flows always approaches the same runway according to a certain hinted trailing order, and the final landing order is gradually formed. Therefore, it is proposed that the trailing relationship determined at FAF be the generalized trailing order throughout the arrival process for all arriving aircraft in the TMA.

(2) Measuring the aircraft headway

First, the concept of the shortest residual time $P^i_{\min}(t)$ from FAF of aircraft i at a certain time t is given. Affected by air traffic controller's cognitive dynamics, the aircraft trajectory may deviate from the preplanned arrival procedures under specific circumstances, and the radar trajectory contains the intention information for the controller's historical guidance. Therefore, a "shortcut" route for the aircraft to subsequently fly to the FAF point can be found in the historical flight trajectories. Let aircraft i at time t be located at point P, then, its shortest residual time $P^i_{\min}(t)$ from the FAF can be determined from the shortest flight trajectory passing by this trajectory point. That is, the shortest residual time $P^i_{\min}(t)$ is equal to the time used in the shortest flight trajectory from the flight trajectory point P to the FAF. As shown in Fig.2, the flight trajectory in red is the shortest flight trajectory that takes the least amount of time to travel from point P to FAF. Therefore, the shortest residual time $P^i_{\min}(t)$ of all aircraft passing by point P is determined by the flight trajectory shown in red.

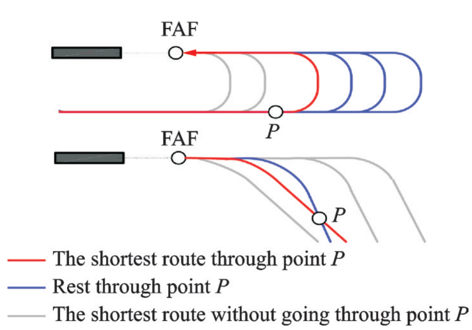

Fig.2 An example of the shortest path corresponding to a given point

As shown in Fig.3, the actual operation flight trajectory data can be used as an example to calculate the $P^i_{\min}(t)$ of a certain aircraft i at time t at the flight trajectory point P. The steps are as follows. (1) Use flight trajectory point P as the center of a circle and designate an area (the green circular area in the figure). (2) Determine the shortest flight trajectory from all flight trajectories passing by the green circular area (the flight trajectory in red is the shortest flight trajectory, the flight trajectories in blue are all that pass by the green circular area, and the flight trajectories in white have not passed by the green circular area). (3) The residual time from the corresponding flight trajectory point on the flight trajectory in red to FAF is the $P^i_{\min}(t)$ of flight trajectory point P.

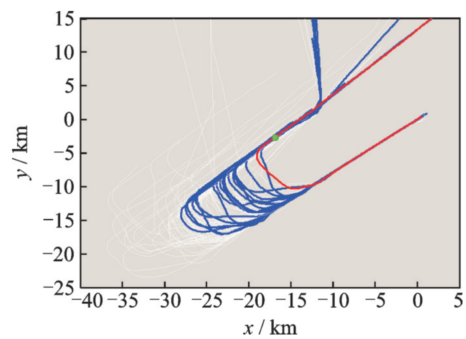

Fig.3 An example of the shortest distance remaining at a certain point

Based on the concept of the shortest residual time $P^i_{\min}(t)$ from FAF, the formula for calculating the generalized headway between two successive aircrafts of i and j at time t can be given as

$$T^{ij}_{\text{spacing}} = P^j_{\min}(t) - P^i_{\min}(t) \tag{1}$$

where aircraft i is the "preceding aircraft" and aircraft j the "succeeding aircraft." A typical and simple example below introduces the concept of the generalized headway for the aircraft. Fig.4 is a simple schematic diagram of two successive aircraft approaching.

From Fig.4, prior to position A, the headway between the two aircraft remains constant because the shortest flight trajectory for the two aircraft is always the same. Starting from position A, the succeeding aircraft begins to deviate from the preceding aircraft's shortest flight trajectory. Therefore, the headway between the two aircraft begins to expand. At position B, the headway has stopped changing and remains constant thereafter.

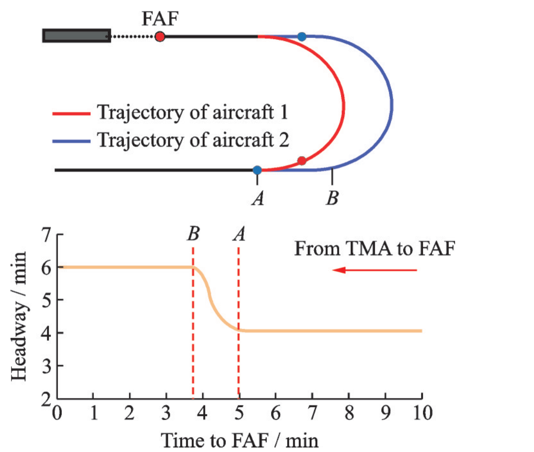

Fig.4 Schematic diagram of calculating the aircraft headway in traffic flow

2 Evolutionary Characteristics of Aircraft Headway

The aircraft headway extracted above is helpful to understand the cognitive characteristics of air traffic controller and the characteristics of arrival traffic flow. The evolutionary characteristics of different control decisions and aircraft headway in different situations are explored in this section.

2.1 Headway evolutionary characteristics for different control decisions

Due to the complexity of traffic operations in TMA, the controller needs to continuously provide radar vectoring, speed adjustment, and orbiting to adjust aircraft headway, thereby completing a series of control decisions, such as aircraft sequencing, conflict resolution, and headway adjustment. Only a stable and smooth headway change process is beneficial for providing safety and efficiency, as well as reducing the fuel consumption. Therefore, the change in the aircraft time interval can reflect the effects of implementing the controller's strategies.

(1) Analysis of the aircraft headway curve under the influence of control decisions

Since the control decisions are the result of the air traffic controller's cognitive process, the aircraft approach sequence is formed gradually, and aircraft headway is also continually changing. In particular, a negative value will appear in the headway. This is a reasonable phenomenon because it indicates that the succeeding aircraft overtakes the preceding aircraft at a certain time. The succeeding aircraft is expected to arrive at the FAF earlier than the preceding one. Later, the sequencing or scheduling decisions will change the arrival order and arrival time. The preceding aircraft gradually overtakes the succeeding aircraft and gradually aligns with the landing sequence results at the FAF. Therefore, the final headway value is still positive.

There is a detailed explanation of the effects of various control decisions on aircraft headway changes. In Fig.5(a), the succeeding aircraft is expected to land before the preceding one, so the headway value of the two aircraft at the beginning is negative. However, the air traffic controller guides the aircraft to deviate from its original planned flight route midway, causing an increase in the headway value, and the preceding aircraft starts to overcome the succeeding one.

In Fig.5(b), the first reduction in aircraft headway is caused by air traffic controllers' orbiting command on the preceding aircraft. Then, the preceding aircraft must be vectored by air traffic controller, causing the aircraft headway decreased, and a second drop appears in the headway.

In Fig.5(c), under the intervention of the air traffic controller, the succeeding aircraft carries out radar vectoring and orbiting. Therefore, the headway between the succeeding and the preceding aircraft is further enlarged. However, the preceding aircraft also executes standard holding procedure, which causes a slight drop in the aircraft headway after a fluctuating rise, but it is stable overall.

In Fig.5(d), the initial trajectories of the two aircraft are basically consistent. Later, the controller schedules the rear aircraft to carry out a deviation maneuver, causing the headway to increase.

(2) Control decision analysis: Headway deviation value

To determine the implementation effect of the control decisions from headway data, a concept for characterizing the performance of the controller's aforementioned control strategies is proposed in this paper, i.e., the headway deviation value. The headway deviation value refers to the difference between the target and the actual time interval of two succes-

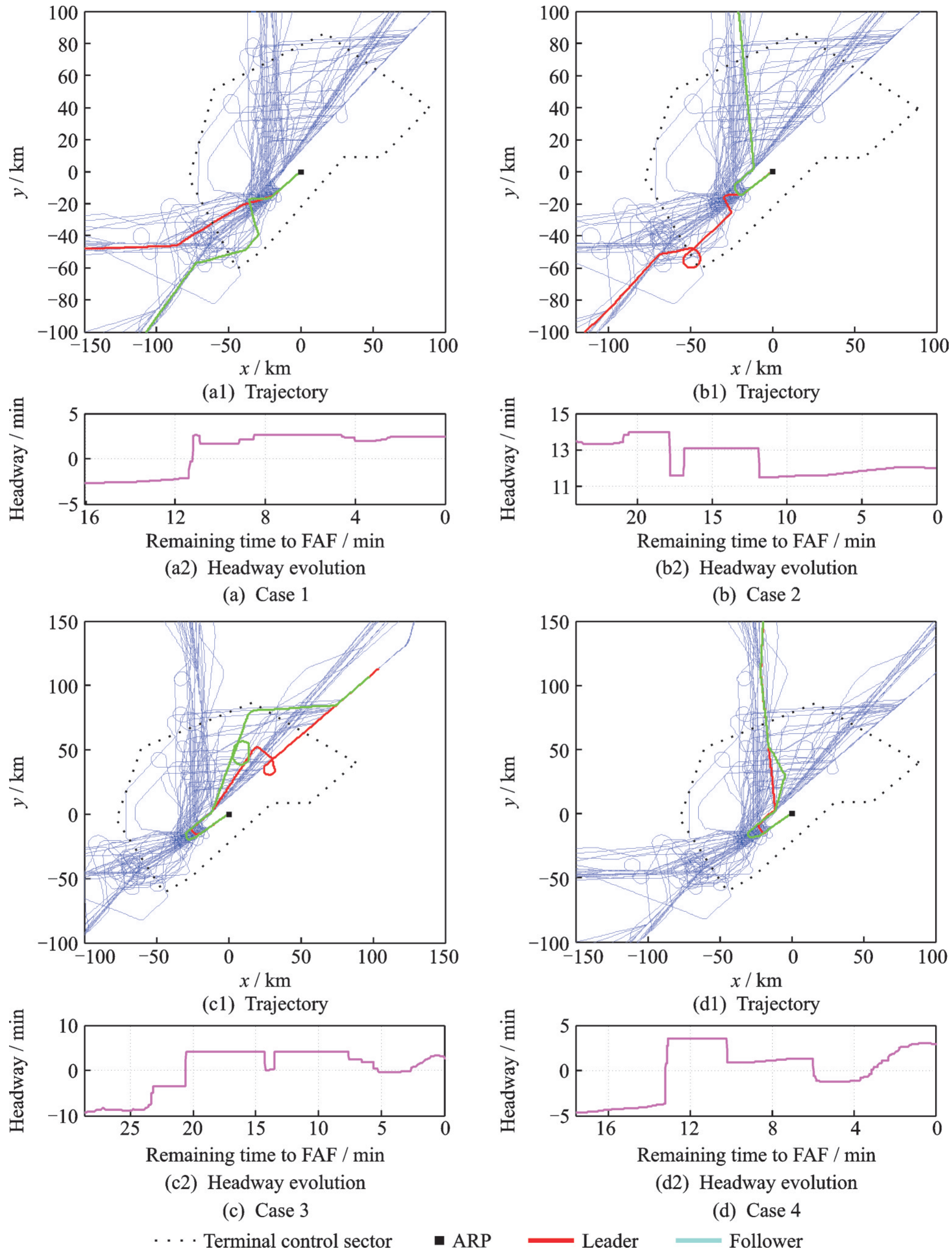

Fig.5 Four cases of aircraft headway evolution process

sive aircraft at each moment during the arrival, where the target time interval refers to the final time interval of the two successive aircraft at FAF. The formula for calculating the headway deviation value is shown as

$$H_d(t)=H(t)-H_0(t) \tag{2}$$

where $H_d(t)$ is the time interval deviation value of the aircraft pair at time t, $H(t)$ the time interval value of the aircraft pair at time t, and $H_0(t)$ the target time interval value of the aircraft pair at time t.

The graph of $H_d(t)$ curve corresponding to the headway data is given in Fig. 6. A headway deviation value equals to zero means that the aircraft headway is equal to the target headway. A negative headway deviation value corresponds to the aircraft headway being smaller than the target headway. A positive headway deviation value illustrates that the aircraft time interval is greater than the target time interval. During the aircraft pair approaching FAF, their headway deviates from the target time dynamically, but the general trend is approaching to zero gradually. The greater the deviation degree and the more frequent the deviation events, the more frequently the controller will change the aircraft speed.

This frequent change in speed or heading causes the aircraft to fly erratically, thereby leading to increased fuel consumption and decreased flight efficiency. In summary, through the headway deviation value, the implementation effects of air traffic control decisions can be characterized in a microscopical, qualitative, and visual manner.

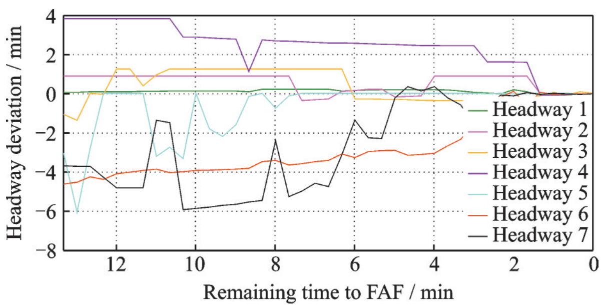

Fig.6 Variation of aircraft headway deviation

2.2 Headway evolutionary characteristics in different phase-states

The aircraft always have to perform orbiting or radar vectoring when the air traffic is crowed. From a macro perspective, the average flight time of the aircraft in terminal areas is much bigger when the air traffic is in congested state. The average flight time of aircraft in congested state is much longer, the average flight time of aircraft in stable state is medium, and the average flight time of aircraft in free state is much shorter. Accordingly, the headway performs different distribution characteristics in different states from the micro perspective. Thus, the air traffic flow can be classified by different characteristics of aircraft headway.

Ref.[16] used different distribution models to integrate the distribution characteristics of different states of the samples, and established the probability density function which can better reflect the different distribution characteristics of the samples. In this paper, normal distribution is used to characterize the headway distributions in congested and steady states, and the negative exponential distribution is used to characterize the headway distributions in free state. By constructing a three-dimensional mixed distribution model of aircraft headway, the relationship between different traffic states and the expected aircraft headway is established. The expected headway of approaching aircraft at the entrance of runway under three phase states is calculated. The expected headway and its deviation under three traffic states are displayed in the form of error diagram, as shown in Fig.7.

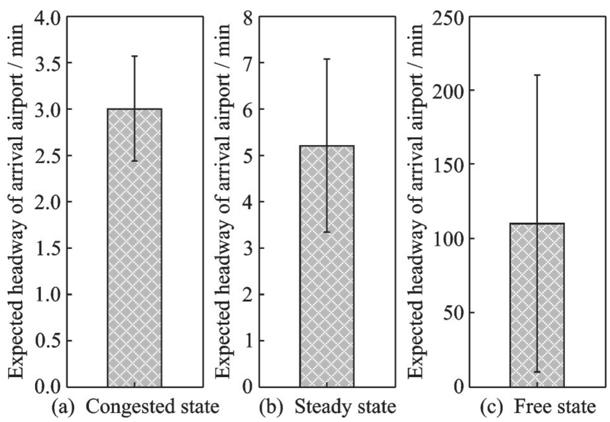

Fig.7 Expected aircraft headway under different traffic states

The flight trajectory data of three sets of trailing aircraft pairs in various states are randomly selected and the time-varying characteristics of headway data are extracted. First, the fluctuation characteristics of the headway data for different traffic states are analyzed. Based on the flight trajectory data of the nine sets of successive aircraft pairs extracted, the actual trajectories and headway variations for each pair of aircraft are plotted (Fig.8).

(1) Congested state

The range of expected headway range for the arriving aircraft near the runway entrance corresponding to the congested state is given in Figs. 8(a)—(c). Then, three sets of successive aircraft with headway values within this range at the FAF are listed as examples, and their flight trajectories and headway variation situations are presented. The figure shows that the motion trajectories of all aircraft in this state deviate more from the standard arrival procedure, i.e., there are more turns and more orbits. Headway changes in congested state have the following characteristics: The aircraft headway fluctuates very frequently and the range is popularly large, but the changes tend to be stable with less fluctuation when aircraft approaching FAF.

In congested state, the interactions between

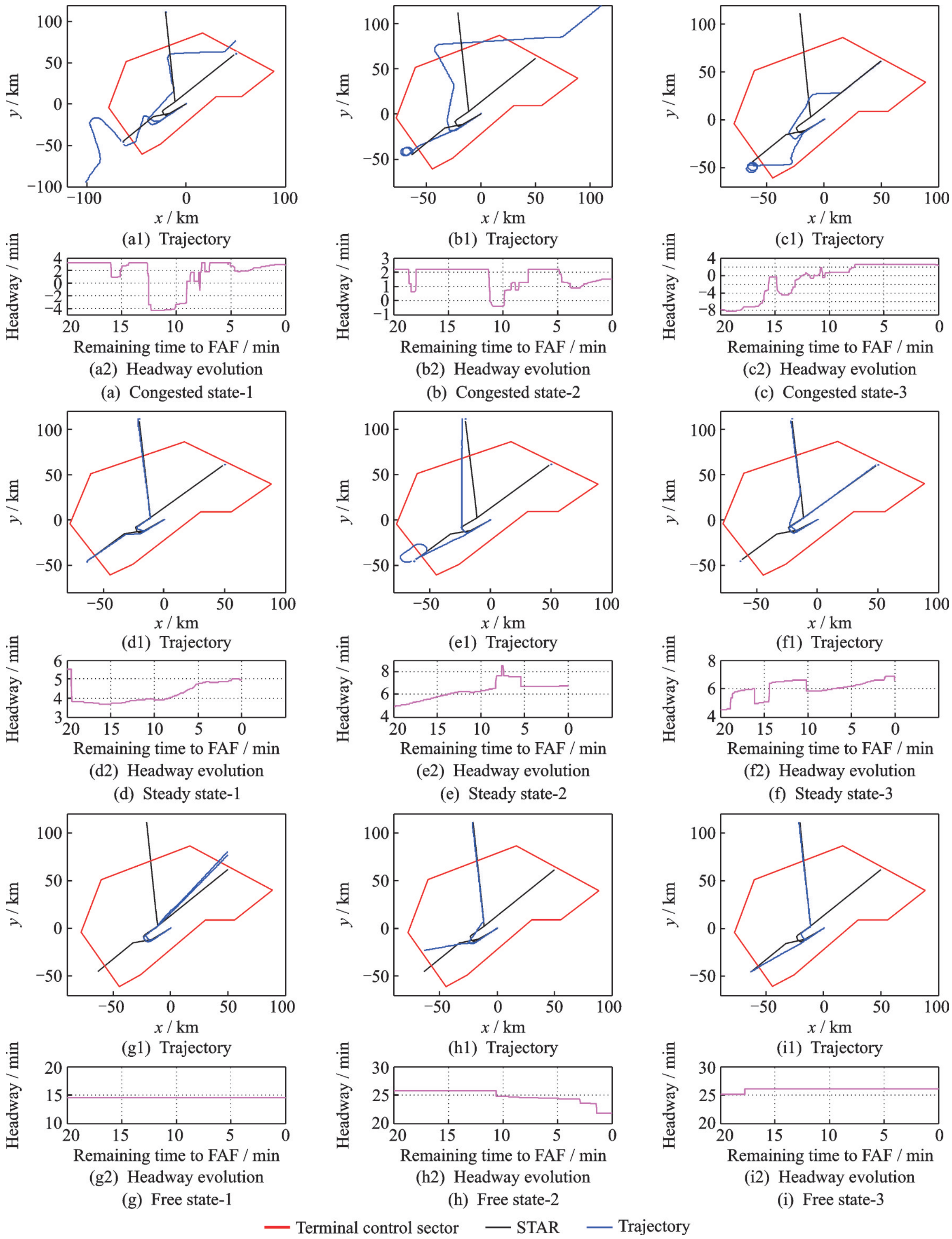

Fig.8 Aircraft headway evolution in different states

the aircraft are further enhanced, and the aircraft-following phenomenon is more obvious. It is not enough for an airplane to adjust its speed. To improve air traffic safety and efficiency, orbiting and radar vectoring are used as well. At this occasion, microscopically, the flight trajectory cluster gradually turns from a convergent to divergent state; microscopically, the flight trajectories show diversity, some flight trajectories deviate drastically from the standard arrival route, and some flight trajectories are obviously extended. In such a situation, the aircraft headway must be changed frequently. The frequent fluctuations in early arrival stage corresponding with the sequence decisions, and after passing by the initial approach fix (IAF) point, the aircraft sequence is basically completed. Therefore, a more stable aircraft headway can be seen in the late arrival stage, with almost no fluctuations.

(2) Steady state

The range of expected headway for arrival aircraft near the runway entrance corresponding to the steady state is given in Figs. 8 (d) — (f). Then, three sets of headway values at the FAF are listed as examples. The flight trajectories and headway variations of the three aircraft pairs are given. The figures show that the most trajectories deviate less from the standard arrival route and there is few orbiting phenomena. Headway changes have the following characteristic: Although greater fluctuations appear temporarily in aircraft headway to a certain extent, it is more stable overall, and there are very few drastic changes.

This is a result of the gradual formation of aircraft queuing. The mutual influence and restrictive function within the arrival traffic flow are gradually enhanced, and the controller must exchange aircraft sequence. The controller will generally maintain the aircraft headway by means of speed adjustment to ensure a safe separation. Aircraft headway is more stable overall, and there are only slight fluctuations caused by the speed adjustment decision.

(3) Free state

The expected headway range for the arrival aircraft in free state is given in Figs. 8(g)—(i). The figures show that all the trajectories in this state have higher adherence with the standard arrival route, and some direct trajectories to FAF appear. Headway changes in free state have the characteristic of being always more stable with very little variation in fluctuation.

Since the traffic density in free state is lower, there is rare conflict between aircraft, and the headway of arriving aircraft is normal large. Therefore, the safety interval requirement can be fully guaranteed, and the flying is relatively not subject to interference. In certain situations, it is even possible to use a straight-line approach without following the standard approach route anymore. In this situation, it is not necessary to issue radar vectoring or speed adjustment instructions to control the headway. And the fluctuation of headway is very small.

To further examine the evolutionary characteristics of headway for different states, the headway deviation value of each aircraft pair is calculated, whose box line diagram is drawn as Fig.9.

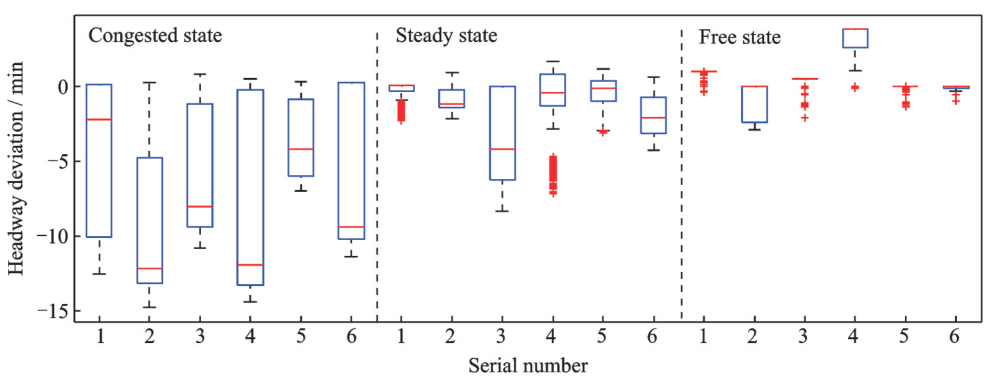

Fig.9 A box line diagram of aircraft headway deviation value

Additionally, the length of the actual trajectory and the extra flight distance for each aircraft are calculated. The extra flight distance is the difference between the length of the actual trajectory and the standard arrival route (Table 1).

For congested state, the headway data deviate largely and distribute widely, which is caused by the high traffic density in TMA. To maintain a safe separation and the landing order, the control decisions such as speed adjustment, altitude adjustment, radar vectoring and orbiting are performed constantly. So, the aircraft headway has strong time-variant characteristics, and the aircraft's extra flight distance is long. For steady state, the degree of divergence in the headway deviation value is relatively small, some outliers begin to appear, and the intervention of arrival traffic is reduced. In free state, the divergence degree in the headway deviation data is the smallest, and the most outliers occur. This is due to the smaller number of flights in the free state. The air traffic controller rarely controls the aircraft under this situation.

Table 1 Extra flight distance of arrival aircraft under various states

State attribution	Serial number of trajectory	Actual trajectory length/km	Length of the flight procedure/km	Extra flight distance/km
Congested state	72	230.213	142.987	87.225
	73	213.652	117.644	96.008
	97	136.074	79.585	56.489
	98	311.978	213.813	98.165
	102	160.740	117.644	43.096
	103	147.554	79.585	67.969
Steady state	36	82.000	79.585	2.415
	37	153.403	163.838	−10.434
	124	141.923	79.585	62.338
	125	152.735	163.838	−11.102
	127	134.938	117.644	17.294
	128	149.100	163.838	−14.737
Free state	40	139.062	122.890	16.172
	41	148.068	127.432	20.636
	81	70.173	79.585	−9.411
	82	160.826	163.838	−3.011
	112	79.121	79.585	−0.463
	113	148.566	163.838	−15.271

Except for a few outliers, most headways basically remain unchanged from arrival to landing, and the extra flight distances are mostly short. In summary, for different traffic states, the headways have clearly different evolutionary characteristics.

3 Conclusions

In this study, we find out that the aircraft headway is an effective index describing air traffic control behaviours. The measurement of aircraft headway is established. The evolutionary characteristics of aircraft headway are analyzed under variety air traffic control behaviours, and the evolutionary characteristics in different traffic states are explored respectively. This study can be expanded for applications in air traffic situation evaluations, capacity assessments, and air traffic control effectiveness evaluations and provides a theoretical basis for further research on aircraft headway.

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Author contributions Prof. **WANG Chao** summarized the existing researches and contributed ideas about empirical exploration of air traffic control behavior. Prof. **LI Shanmei** conducted the analysis and wrote the manuscript. Mr. **ZHU Ming** contributed to the data mining and modified the manuscript.

Competing interests The authors declare no competing interests.

(Production Editor: WANG Jing)

终端区空中交通管制行为的实证研究:从空中交通流的角度

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摘要:在大容量、高密度的交通背景下,空中交通表现出流体状的微观特征。这些特性是由单个飞行器之间的尾随作用形成的。机头时距是指在空中交通流中连续飞行的飞机之间的时间间隔,是空中交通流最重要的特征之一。机头时距的变化揭示了空中交通管制行为。本文通过对终端区雷达航迹进行分析,研究了空中交通管制行为的特点。本文在确定了飞机之间的尾随关系后,对进场交通流的机头时距进行测量。讨论了不同控制策略下的机头时距演化特性和不同相态下的机头时距演化特性,得到了一些有趣的结果。本文的工作将有助于学者和管理者了解空中交通流的本质,开发空中交通管理的智能辅助决策系统。

关键词:空中交通;机头时距;交通状态;空中交通管制