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The Lateral Conflict Risk Assessment for Low-altitude Training Airspace using Weakly Supervised Learning Method

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ABSTRACT
The lateral conflict risk assessment of low-altitude training airspace strategic planning, which is based on the TSE errors has always been a difficult task for training flight research. In order to effectively evaluate the safety interval and lateral collision risk in training airspace, in this paper, TSE error performance using a weakly supervised learning method was modelled. First, the lateral probability density function of TSE is given by using a multidimensional random variable covariance matrix, and the risk model of a training flight lateral collision based on TSE error is established. The lateral conflict risk in specific training airspace is analyzed, and then the lateral collision model is built. Through the quantification of the risk probability of lateral collisions, the security level of a specific airspace is evaluated. The analysis of the examples shows that for normal training flight in a variety of 4D flight track data, the lateral collision risk in specific training airspace is 0.543744×10^{-13} , the conflict risk meets the requirement of safety target level of international civil aviation organization.

KEY WORDS: Air traffic control, Lateral conflict risk, Low-altitude complex flight, Standard safety interval, TSE

1 INTRODUCTION

CHINA is one of the fastest growing aviation industries in the world. At present, China is witnessing a strong demand in its air transport. As the development expands, it is estimated that by the end of the "Thirteenth-Five-year plan", the transport airports will reach 270 or so. There will be approximately 4600 cargo airplanes and 5,000 general planes, and a total of nearly 10,000 airplanes will be realized in the civil aviation fleet. This undoubtedly brings new opportunities and challenges to China's civil aviation pilots training. With the rapid development of China's civil aviation industry, the exposure of aircraft used in the pilots training in low-altitude complex flight conditions, combined with a large number of training hours and strict safety flight requirements, aircraft lateral conflict risk research has become particularly important.

The aircraft flight safety under complex conditions is always of intriguing interest as well as difficulty in international aviation research. In addition, the flight accident rate of aircraft under complex conditions is ten times more than that of a normal flight. The difficulty of realizing a safe flight in a low-altitude complex flight condition is that it is subjected to complex environmental factors such as; diverse terrain and obstacles, extreme weather and so on. Moreover, the high intensity and concentration of various training aircraft within a limited airspace leads to a more frequent occurrence of lateral collision risk for aircraft in the same altitude. Along with the development of air traffic management techniques and flight training techniques, the lateral error of aircraft, in particular the total systematic error (TSE) associated with the aircraft's ability to maintain track and navigation positioning errors in training flights, is increased in importance for investigation. How training aircraft’s TSE error performance can ensure flight safety and achieve training results has become the hotspot for current air traffic control and flight training research.

At present, a lot of research work has been done on TSE lateral collision. British scholar (Reich P.G, 1966) put forward the aircraft longitudinal, lateral, vertical

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collision risk model, which is the early research of this field. (Russell A, 1996) (Heinz, 1996) of the NASA Ames Research Center look into accounts of the influence of various uncertainties and assumed, according to the central limit theorem, the position error of the track is a probabilistic ellipsoid. In the lateral conflict probability analysis, (Yang, et.al. 1997) analyzed the error distribution of each stage. Russell established a model of the probability-based position prediction error, and integrated the conflict domain to obtain the collision probability. (Hu, et.al. 2005) took the influence of airborne wind and other uncertain factors on flight into dynamic equation. (Yang, et.al. 2004) used the probability estimation method of aircraft intention information in the track prediction model. Chinese scholars have also carried out relevant researches. (Li, et.al. 2004) made preliminary research on the Reich model of colliding risk of parallel route and conducted modelling and relevant analysis. (Chen, et.al. 2002) (Wang, et.al. 2004) used a probability-based collision detection algorithm to analyze the collision probability based on Brownian motion, and obtained the effect of various factors on the probability of conflict. On this basis, the algorithm is extended to three dimensions, and the flow of practical application is given. (Zhao, et.al. 1998) studied the frequency of a dangerous collision of aircraft on two cross-routes, and proposed the concept of dangerous collision/collision zone. However, the research on the collision risk of TSE errors, especially in training flight, is still in the initial exploration stage. Previous studies only consider the effects of one or both of the track definition error (PDE), flight technology error (FTE) and navigation system error (NSE) (ICAO DOC 9689) (Zhao, et.al. 2016) (Zhu, et.al. 2014).

This paper is organized as follows. Section 2 presents an overview of collision risk modelling approaches. The risk of a lateral conflict under the low-altitude complex training flight condition and the TSE localization error is modelled and discussed in Section 3. Firstly, the TSE localization errors in the flight path data are analyzed, and the distribution function of the lateral localization error is given by the covariance matrix of the 3D random variables. In the specific analysis of the composition of TSE error, the probability of lateral overlap of the two planes in the training flight and the lateral conflict risk in the airspace of the low-altitude training are obtained in Section 4. The validity of the lateral flight conflict model for the risk assessment in low-altitude training airspace strategic planning is verified by examples. Finally, results and conclusions are given in Section 5.

2 RISK MODELLING APPROACHES

2.1 Overview of Risk Modelling Approaches

ONE of the principal matters of concern in the daily operation of civil aviation is prevention of conflicts between aircraft, either while airborne or on the ground, which might escalate to collision. Although aircraft collisions have actually been very rare events, contributing to a very small proportion of the total fatalities, they have always caused relatively strong impact mainly due to relatively large number of fatalities per single event and occasionally the complete destruction of the aircraft involved.

The main driving force for developing risk methods/models during the 1960s was the need for increasing airspace capacity over the Atlantic through decreasing aircraft separation minima. In general, separating aircraft using space and time separation standards (minima) has prevented conflicts and collisions. However, due to the reduction of this separation, in order to increase capacity and thus cope with growing air transport demand, assessment of the risk of conflicts and collisions under such conditions has been investigated using several important methods/models. The methods/models were expected to show if a reduction of separation and spacing between flight tracks would be sufficiently safe, i.e., determine the appropriate spacing between tracks guaranteeing a given level of safety.

- The Reich–Marks model was developed in the early 1960s by the Royal Aircraft Establishment, UK (Reich, 1966). It is based on the assumption that there are random deviations of both aircraft positions and speeds from the expected. The model was developed to estimate the collision risk for flights over the North Atlantic and consequently to specify appropriate separation rules for the flight trajectories (Shortle et al., 2004). The model computed the probability of aircraft proximity and the conditional probability of collision given the proximity (Machol, 1995; FAA/EUROCONTROL, 1998).
- The Machol–Reich model was developed after the ICAO had established the NAT SPG (North Atlantic System Planning Group) in 1966 with the idea of developing the Reich-Marks model as a workable tool, as well as to increase of airspace capacity. Consequently, the ICAO NAT SPG adopted the threshold for risk of collision of two aircraft due to the loss of planned separation (Machol, 1975, 1995).
- Intersection models belong to the simplest collision risk models. They are based on the assumptions that aircraft follow pre-determined crossing trajectories at constant speeds. The probability of a collision at the crossing point is computed using the intensities of traffic flows on

each trajectory, aircraft speeds, and airways geometry (Siddiqee, 1973; Schmidt, 1977; Hsu, 1981; Geisinger, 1985; Barnett, 2000).

- Geometric conflict models are similar to intersection models. In these models (developed in 1990s) the speed of any two aircraft is constant, but their initial three-dimensional positions are random. The conflict occurs when two aircraft are closer than the prescribed separation rules (Paielli and Erzberger, 1997, 1999; Irvine, 2002; Alam et al., 2009; Chaloulos et al., 2010；Oscar et al., 2014).
- The generalized Reich model was developed by removing restrictive assumptions from the Reich model based on the fact that Reich model does not adequately cover certain real air traffic situations. Such a generalized collision model was developed during 1990s and has been in use as part of the TOPAZ (Traffic Optimization and Perturbation AnalyZer) methodology (Blom et al., 1998, 2003; Shortle et al., 2004; Blom and Bakker, 2002).

Collision risk methods/models have gradually been developed from Marks, Reich and Machol to the latest versions used in the TOPAZ methodology. The main purpose has always remained to support decision-making processes during system planning and development, through evaluation of the risk and safety of the proposed changes (either in the existing or the new system).

2.2 Risk Modelling Approach Accepted by ICAO

The International Civil Aviation Organization (ICAO) has developed the Collision Risk Model (CRM) as a mathematical tool used in predicting the risk of mid-air collision. During development of CRM ICAO adopted the Reich (1966) and Hsu (1981) formulae (ICAO, 1998, 2002, 2009) and further defined a unified framework for derivation of collision risk models, called the Rice formula (Mehadhebi and Lazaud, 2004; ICAO, 2009). From the Rice formula it is possible to derive the Reich and the Hsu formulae (Mehadhebi and Lazaud, 2004).

ICAO has adopted the CRM model as a crucial part of the Airspace Planning Methodology for determination of separation criteria (ICAO, 1998). The main purpose of the methodology is determination of separation minima based on collision risk modelling. Calculated collision probability based on CRM is used for comparison with the reference system (if it exists) or for evaluation of the system risk against a threshold, the so-called Target Level of Safety (TLS).

According to ICAO Circular 319 (2009), “the purpose of collision risk models in the context of the determination of separation minima is to model the chain of events leading a pair of initially separated aircraft to a collision”. ICAO CRM calculates probability of collision as the lateral or vertical overlap probability, given probability density functions of position errors at a given moment (where position error depend on path definition error, flight technical error, navigation system error and surveillance error) (Mehadhebi and Lazaud, 2004; Fujita, 2009). However, Mehadhebi (2007) pointed out that CRM’s from ICAO Doc. 9689 (1998) are not sufficient for modelling all situations, especially operational errors.

3 FLIGHT CHARACTERISTICS AND LATERAL CONFLICT MODEL USING WEAKLY SUPERVISED LEARNING METHOD

AT present, in monitoring flight training, radar monitoring technology is widely used as the core scheme, and the collision detection is carried out for the low-altitude objective safety factors between the aircraft, the aircraft and the terrain, the aircraft and the meteorology. Whether the total system error (TSE), associated with the aircraft’s ability to maintain track and navigation location errors in training flight, can ensure flight safety and achieve training effectiveness has become a hot topic in field of air traffic control and flight training.

In addition, civil aviation flight training has its unique characteristics. Pilots should perform the training with primary, intermediate or advanced trainer aircraft, in designated training airspace and at the designated training altitude, and in accordance with the pre-established training flight plan. Training airspace and height are all restricted to low-altitude, while subjects for training are all types of trainer aircraft, which are heterogeneous aircraft because of their diverse flight performances. Furthermore, pilots’ lack of relevant flight skills and experiences brings many uncertainties.

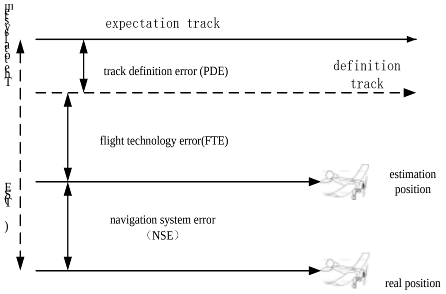

Figure 1. **Lateral TSE Composition.**

3.1 Analysis of Lateral Conflict Factors

Aircraft lateral position error is related to the aircraft’s ability to maintain track and navigation positioning errors and other factors, represented by the total system error (TSE). TSE contains three aspects of error, namely, track definition error (PDE), flight technology error (FTE) and navigation system error (NSE), as shown in Figure 1.

Since the three errors are vector-distributed in space, TSE is the vector sum of three errors, and the standard deviation of TSE is the square root of the sum of squares of the standard deviations of these three errors

$$TSE = \sqrt{PDE^2 + FTE^2 + NSE^2}\ , \tag{1}$$

Because of the influence of a variety of factors, aircraft flying in the training airspace may be unable to fly along the scheduled training routes, thus leads to yaw. Among the many factors that affect collision risk, the collision risk is a function of its TSE error, and the acceptability of the risk depends on the safety target level (TLS) of the specific airspace. When the TLS is determined, the minimum TSE error criterion for a particular airspace is determined. The training mission must meet its minimum standards to ensure flight safety.

3.2 TSE Lateral Conflict Model

The flight positioning error caused by PDE, FTE, and NSE error performance is one of the main reasons for the yawing of the training aircraft flying under the TSE error performance environment. Lateral yaw occurs most frequently, but is most likely to be overlooked by pilots. As the flight time increases, if the two planes flying in the specific training space at the same altitude don't adjust their lateral yaw, and after a certain period of time, the lateral separation between them will be less than the horizontal safe separation, and the risk of a lateral collision will occur, as shown in Figure 2.

Supposing the following conditions are satisfied for the lateral collision model; two aircraft fly in the same training space and at the same altitude; the TSE error performance of the two aircraft is independent, that is, they are independent in the lateral, longitudinal and vertical directions; the yawing speed of the aircraft is independent of its position, and without considering the impact of ground control on the risk of collision.

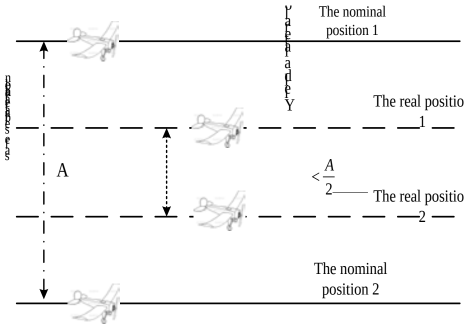

Figure 2. **Two Planes with the Same Direction & Altitude.**

It is assumed that the error of direction finding positioning caused by the error of track definition, flight technique error and navigation system error are $X_{PDE}, X_{FTE}, X_{NSE}$, and they obey normal distribution (ccar-141, 2004)

$$\begin{aligned} &X_{PDE} \sim N(\mu_1, \sigma_1^2) \\ &X_{FTE} \sim N(\mu_2, \sigma_2^2) \\ &X_{NSE} \sim N(\mu_3, \sigma_3^2)\ , \end{aligned} \tag{2}$$

In general, the resulting direction finding error caused by $X_{PDE}, X_{FTE}, X_{NSE}$ is interrelated. The correlation coefficients are as follows: ρ_{12} the correlation coefficient between the track definition error (PDE) and the flight technology error (FTE); ρ_{23} the correlation coefficient between the flight technology error (FTE) and the navigation system error (NSE); ρ_{13} the correlation coefficient between the track definition error PDE and the navigation system error NSE.

According to $\rho_{12}, \rho_{23}, \rho_{13}$, the covariance matrix of the three-dimensional random variable M is obtained

$$C = \begin{bmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \rho_{13}\sigma_1\sigma_3 \\ \rho_{12}\sigma_1\sigma_2 & \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 \\ \rho_{13}\sigma_1\sigma_3 & \rho_{23}\sigma_2\sigma_3 & \sigma_3^2 \end{bmatrix} \tag{3}$$

$$M = (X_{PDE}, X_{FTE}, X_{NSE})\ , \tag{4}$$

The probability density function of the three-dimensional random variable M is

$$f(X_{PDE}, X_{FTE}, X_{NSE}) = \\ \frac{1}{(2\pi)^{3/2}[\det(C)]^{1/2}} \exp[-\frac{1}{2}(X-\mu)^T C^{-1}(X-\mu)] \tag{5}$$

$$X = \begin{bmatrix} X_{PDE} \\ X_{FTE} \\ X_{NSE} \end{bmatrix}, \mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \end{bmatrix}, \tag{6}$$

$\det(C)$ is the determinant of C, C^{-1} is the inverse matrix of C

This paper only considers the lateral error caused by the total system error (TSE). If the lateral yawing distance caused by TSE is more than half of the lateral spacing standard A , the two aircraft will overlap laterally. Calculation shows the probability of lateral overlap of two aircraft:

$$P = \iiint_{|X_{PDE}+X_{FTE}+X_{NSE}|\le\frac{A}{2}} f(X_{PDE}, X_{FTE}, X_{NSE})$$
$$dX_{PDE}dX_{FTE}dX_{NSE} \tag{7}$$

According to Bibliography (Zhao, et.al. 2016), it can be known that the lateral conflict risk of two aircraft is

$$C_{risk} = 2N \cdot P \tag{8}$$

Where N is the number of studied aircraft in the low-altitude airspace.

At this time, the aircraft's risk of lateral collision in low-altitude airspace is

$$C_{risk} = 2NP = 2N \cdot \iiint_{|X_{PDE}+X_{FTE}+X_{NSE}|\le\frac{A}{2}} f(X_{PDE}, X_{FTE}, X_{NSE})$$
$$dX_{PDE}dX_{FTE}dX_{NSE} \tag{9}$$

In the TSE components, PDE can be reduced by high-precision measurements. Without compromising the generality of the PDE, constraints and control of the PDE are mainly realized through measurements of the coordinates of key points, such as obstacles around airport terminal area and entrances of runway center line, which is achieved by using high-precision measurement equipment based on WGS-84 system before designing the flight program. If PDE has been measured, low-level flight of two aircraft lateral error discussion can usually ignore PDE. Thus, TSE is controlled by the flight technology error FTE and the navigation system error NES.

When ignoring PDE, FTE and NSE should be constrained respectively to control the TSE.

The same assumption is made; X_{FTE}, X_{NSE} obey normal distribution.

$$X_{FTE} \sim N(\mu_2, \sigma_2^2)$$
$$X_{NSE} \sim N(\mu_3, \sigma_3^2) \tag{10}$$

In general, the lateral positioning errors caused by X_{FTE}, X_{NSE} are interrelated and the correlation coefficient ρ_{23} represents the correlation coefficient between the flight technology error FTE and the navigation system error NSE.

The covariance matrix of the two-dimensional random variable M' is

$$C = \begin{bmatrix} \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 \\ \rho_{23}\sigma_2\sigma_3 & \sigma_3^2 \end{bmatrix} \tag{11}$$

$$M' = (X_{FTE}, X_{NSE}) \tag{12}$$

C^{-1} is the inverse matrix of C

$$C^{-1} = \frac{1}{\sigma_2^2\sigma_3^2 - (\rho_{23}\sigma_2\sigma_3)^2}$$
$$\begin{bmatrix} \sigma_3^2 & -\rho_{23}\sigma_2\sigma_3 \\ -\rho_{23}\sigma_2\sigma_3 & \sigma_2^2 \end{bmatrix} \tag{13}$$

And $\det(C)$ is the determinant of C

$$\rho_{XY} = \frac{\operatorname{cov}(XY)}{\sqrt{D(X)}\cdot\sqrt{D(Y)}}$$
$$= \frac{E(XY) - E(X)E(Y)}{\sqrt{D(X)}\cdot\sqrt{D(Y)}} \tag{14}$$

The probability density function of the two-dimensional random variable M' is

$$f(X_{FTE}, X_{NSE}) = \frac{1}{2\pi[\det(C)]^{1/2}}$$
$$\exp[-\frac{1}{2}(X-\mu)^T C^{-1}(X-\mu)] \tag{15}$$

The probability of lateral overlap of two aircraft is

$$P = \iint_{|X_{FTE}+X_{NSE}|} f(X_{FTE}, X_{NSE})dX_{FTE}dX_{NSE}$$
$$= \iint_{|X_{FTE}+X_{NSE}|} \frac{1}{2\pi[\det(C)]^{1/2}}$$
$$\exp[-\frac{1}{2}(X-\mu)^T C^{-1}(X-\mu)]dX_{FTE}dX_{NSE} \tag{16}$$

Similarly, the lateral conflict risk of two aircraft is

$$C_{risk} = 2N \cdot P \tag{17}$$

where N is the studied number of aircraft in the low-altitude airspace.

At this time the lateral conflict risk of airplanes in low-altitude airspace is

$$C_{risk} = 2NP$$
$$= 2N \cdot \iint_{|X_{FTE}+X_{NSE}|\le\frac{A}{2}} f(X_{FTE}, X_{NSE})dX_{FTE}dX_{NSE} \tag{18}$$

4 ANALYSIS OF THE FLIGHT LATERAL COLLISIONS BASED ON TSE ERROR

IT analyzes the ADS-B/GPS flight data of the track of circle procedure and eight character procedures of a Cessna 172G1000 primary trainer aircraft in local training. (As shown in Fig. 3, 4 & 5).

Figure 3. Cessna 172G1000 Primary Training Aircraft.

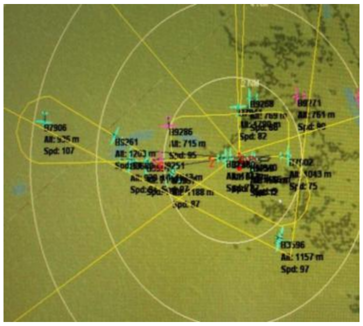

Figure 4. ADS-B Display Information of the Track of Circle and Eight Character Procedures.

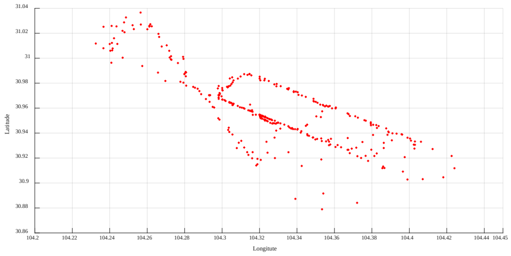

Figure 5. GPS Track Point Flight Data of the Track of Circle Procedure and Eight Character Procedure.

Through the long-term training flight observation, the statistical analysis of the 1254 measurements of the track of circle procedure and 854 measurements of eight character procedures as shown in Fig. 6 & 7.

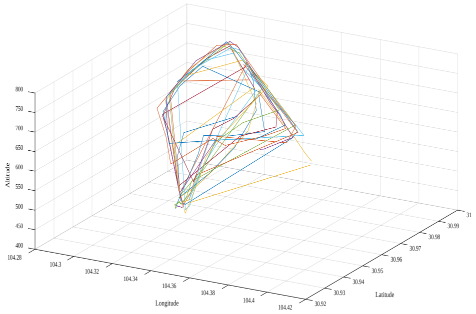

Figure 6. Circle Procedure Fly Track in 4D.

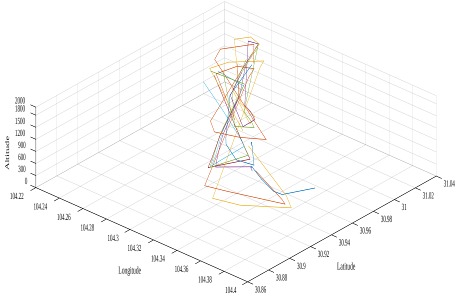

Figure 7. Eight Characters Procedure Fly Track in 4D.

X_{FTE} and X_{NSE} obeys normal distribution, and the error distribution is as follows.

$$X_{FTE} \sim N(7.1684, 4.9102^2)$$

$$X_{NSE} \sim N(0, 4^2) \tag{19}$$

Correlation coefficient $\rho_{23} = 0.5$

The covariance matrix of the two-dimensional random variable M' is

$$C = \begin{bmatrix} 24.1101 & 9.8204 \\ 9.8204 & 16 \end{bmatrix} \tag{20}$$

$$M' = (X_{FTE}, X_{NSE}), \tag{21}$$

$$C^{-1} = \begin{bmatrix} 0.0553 & -0.0339 \\ -0.0339 & 0.0833 \end{bmatrix} \tag{22}$$

$$\det(C) = 289.3213 \tag{23}$$

The probability density function of the two-dimensional random variable M' is (as shown in Fig. 8)

$$f(X_{FTE}, X_{NSE}) = \frac{1}{2\pi[289.3213]^{1/2}} \exp[-\frac{1}{2}(X-\mu)^T C^{-1}(X-\mu)] \tag{24}$$

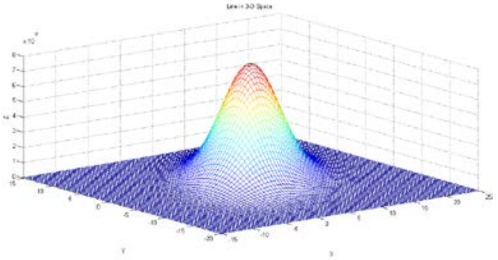

Figure 8. FTE, NSE Probability Density Function of Long-term Training Flight of a Flight Training Institution.

In the local training of a flight training institution, there are 32 aircraft in one flight brigade to perform training tasks, and the number of aircraft $N = 16$. Clearance time interval controlled by ground controllers is one minute to one and a half minutes, and the ground monitoring training terminal area is $30 \times 30 km^2$. Cruise speed for Cessna 172 is $80kt$, and safety separation for two aircraft is $2.5km$. When a single aircraft separation is less than $1.25km$, it can be regarded as violating the minimum safe separation.

Then the probability of lateral collision of two aircraft is

$$\begin{aligned} P &= \int_{29.25}^{30} \int_{23.5}^{24} f(X_{FTE}, X_{NSE}) dX_{FTE} dX_{NSE} \\ &= 1.6992 \times 10^{-15} \end{aligned} \tag{25}$$

The lateral conflict risk of two aircraft is

$$\begin{aligned} & C_{risk} = 2NP = 2N \cdot \\ & \iint_{|X_{FTE} + X_{NSE}| \le \frac{A}{2}} f(X_{FTE}, X_{NSE}) dX_{FTE} dX_{NSE} \\ & = 5.43744 \times 10^{-14} \end{aligned} \tag{26}$$

Comparing the risk value of the two-plane collision risk based on the TSE error with the predetermined safety target level (the ICAO target safety level is 5.0×10^{-9}), it can be obtained that the current flight training safety level, which is under the lateral safety clearance standards and the existing TSE performance, meets the pre-defined safety target level requirements.

5 CONCLUSIONS

Under low-altitude complex training flight, the total system error TSE has seriously affected keeping safe separation and the reliability and safety of flight situation monitoring, and has become one of the main reasons for accidents.

This paper discusses flight lateral conflict risk assessment for low-altitude training airspace using a weakly supervised learning method by applying TSE error performance. First, a risk model of flight lateral conflict, based on TSE error, is established by covariance matrix of multidimensional random variables, and through calculating the collision risk of the planes with same directions in the same training space is obtained. Comparing it with ICAO's predetermined safety target level, a safety assessment of the training airspace can be carried out. Then, in the analysis of examples, the collision risk probability derived from the TSE models is compared with the ICAO's predetermined safety objective, which further improves the training airspace safety assessment. This method can make a scientific assessment of the safety level of the low-altitude training airspace or busy terminal area. It can also verify whether FTE, NSE error level meet the safety requirements.

Since the current study on FTE data statistics and reasons is still incomplete, more in-depth research is required in this field. In conclusion, the lateral collision models established in this paper lay a solid foundation for further study of collision risk at low-altitude complex flight conditions.

6 ACKNOWLEDGMENT

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