Single Runway Landing Vortex Separation Analysis

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Keywords: wake vortex, dissipation, air traffic management, wake interval, risk analysis

Abstract: This paper introduces the generation and influence of the wake, gives the evolution and dissipation model of the wake, analyzes the force of the rear machine into the front machine, and uses the former B747 and the rear B737 as examples, using MATLAB to the front wake vortex. The flow is calculated, and the wake dissipative empirical model is used as the dissipative model for the analysis. The current wake interval is analyzed to prepare for a safe and efficient approach wake interval. The simulation results show that the different dissipation rates have different effects on the wake, and the higher the dissipation rate, the smaller the interval required by the front and rear machines.

1. Introduction

Since the middle of the 20th century, with the increasing maturity of aircraft manufacturing technology, the practicality of civil aviation transportation has increased day by day. The airport's ability to take off and land has limited the number of flights. Therefore, airport capacity has become a bottleneck restricting the development of air transportation. Studying the evolution characteristics and laws of the wake vortex and establishing the vortex separation prediction system are of great practical significance for improving the capacity of existing airports and alleviating the pressure of air traffic.

In the study of vortex, the United States was the first to recognize and engage in research on vortex. In 1969, as part of the Federal Aviation Administration's (FAA) experimental program, Boeing began investigating the vortex and directly comparing the vortex effects of B737 and B707 through flight experiments [1]. In 1975, the FAA began to study the problem of surface wind and vortex positioning. In 1995, the FAA and the National Aeronautics and Space Administration (NASA) established a vortex research project team to collate and research vortex detection and surveillance technologies [2]. In 1997, NASA developed the vortex spacing system [3], and in the same year the European Navigation Safety Organization (EUROCONTROL) initiated the vortex warning system [4]. In 1999, based on the FAA and EUROCONTROL vortex separation studies, application experience and model classification recommendations, the International Civil Aviation Organization (ICAO) officially issued the vortex spacing standard [5]. In 2012, the FAA implemented a new vortex safety separation standard classified according to six models [6-9].

Compared with the study of vortex in the United States [10], Europe [11] and Japan [12], China started late and is accelerating related research.

2. Wake vortex evolution and dissipation

2.1 Parameters of the wake vortex

During the flight, the vortex surface falling off the trailing edge of the wing passes through the near-field evolution phase or the rolling-up phase. Form a wake vortex. The vortex of the aircraft is usually expressed by three parameters: the initial loop Γ_0, the initial vortex core radius r_{c0}, and the initial vortex pitch b_0. According to kutta joukowsky's law [13],

$$\Gamma_0 = \frac{L}{\rho V s B} \tag{1}$$

  DOI: 10.25236/icemit.2019.030

In the equation,L is the lift of the wing. ρ is the air density. V is the flight speed of the aircraft. B is the aircraft wingspan.s is the lateral distribution coefficient of the wing pressure.

For aircraft with a wing distribution with elliptical pressure distribution, $s = \pi/4$,while the wing pressure distribution of a civil aircraft is like an elliptical distribution, most aircraft $s \approx 0.8$ at medium angles of attack, and during the approach, lift Equal to gravity. So Γ_0, b_0 can be approximated by the elliptical wing hypothesis [14],

$$\Gamma_0 = \frac{4Mg}{\pi\rho VB}, b_0 = \frac{\pi}{4}B \tag{2}$$

In the equation, M is the mass of the aircraft; g is the acceleration of gravity, taking $9.8m/s^2$.

2.2 Dissipation of the wake vortex

During the period of continuous evolution after the formation of the wake vortex, its intensity does not change much, is like its initial intensity, and then dissipates at a very fast rate in the later time, and the intensity is also rapidly reduced. The empirical model of vortex dissipation based on experience is as follows [15]:

$$\Gamma(t) = \Gamma_0 \quad t \le t_1$$
$$\Gamma(t) = \Gamma_0\,(t_1 t)^n \quad t > t_1 \tag{3}$$

$\Gamma(t)$ is the intensity of the vortex at time t; t_1 is the time at which the vortex maintains the initial intensity, and n is the dissipation rate, a parameter greater than one. Generally, n is 1.1 in the case of weak dissipation, 1.5 in the case of medium dissipation, and 1.9 in the case of strong dissipation.

For the continuous maintenance of the initial intensity time t_1, since there are too many random factors affecting the dissipation of the wake vortex, it can be regarded as a random variable obeying the normal distribution, and its mean value is t_1. Table 1 shows the value of the wake vortex dissipation parameters obtained by long-term observation of various common models by the John.A.Vlope Research Center of the FAA:

Table 1. Parameters of the wake vortex dissipation model for several typical models

Aircraft category	Landing phase		Takeoff phase		Under very small probability (ε=0.001)	
	σ	t1	σ	t1	Landing	Takeoff
B737	12.1	23.7	6.3	24.6	70.2	44.1
DC-10	12.7	34.9	10.3	31.6	74.3	63.3
B747	11.1	40.0	14.4	40.2	84.4	84.7

ε=0.001 in the table indicates the probability level, which means that in the random dissipation of 1000 wake vortices, the time t_1 at which the wake vortex maintains the initial intensity reaches the value shown in the table.

3. Risk analysis

The basic equation of the maximum roll control torque of the aircraft depends on the wing span of the wing (b^j), the airfoil area (S^j), the air density (ρ), the aircraft's vacuum speed (V^j), and the maximum steady-state rolling rate (p^j) and roll damping coefficient (C_{rd}^j), and give the following equation [16]:

$$M_{control}^j = -\rho\frac{S^j(b^j)^2}{4}V^j C_{rd}^j p^j \tag{4}$$

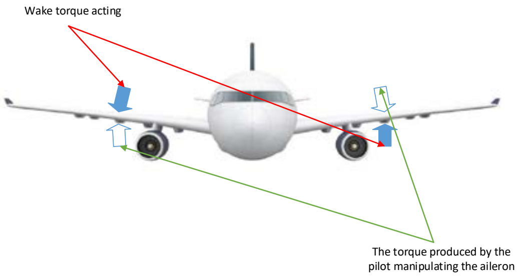

Fig. 1. Analysis of the force of the pilot when the pilot controls the aileron

Considering that when the rolling vortex formed by the wake vortex on the wing causes the aircraft to roll, the pilot must take steps to manipulate the aileron of the aircraft to generate the opposite force to counteract the force of the vortex. In theory, when the pilot's maneuvering aircraft produces a working torque greater than the vortex's acting torque, the aircraft's rotation can be controlled, thereby restoring the aircraft's attitude and ensuring flight safety. However, when the moment of action of the vortex exceeds the force generated by the pilot maneuvering the aircraft, the pilot loses control of the aircraft and is in danger. When the pilot's maneuvering aircraft produces a working torque equal to the vortex's acting torque, the aircraft is in a critical state due to the force balance, and the aircraft no longer rolls. However, considering the actual situation, due to factors such as the inertia of the motion and the reaction of the pilot (usually using a reaction time of 1 second), the aircraft has been deflected at a certain angle, even if the pilot takes certain measures to prevent the aircraft from continuing to deflect, but The already formed side slip angle will cause the aircraft to no longer maintain its original heading flight, at which point we believe that the aircraft is in an unsafe state.

4. Example analysis

Take B737-300 followed by B747-400 as an example to calculate the vortex separation between the two machines. The relevant parameters for calculating the B747-400 model are as follows:

Table 2. Related parameters of the B747-400 model

Aircraft Type	Wingspan(B)	No-load Weight	Air Density(ρ)
B747-400	64.4m	178,756kg	$1.11 kg/m^3$

Considering the calculation of the vortex at landing, the landing weight of the B747-400 is 280,000 kilograms. Assuming a final approach speed of $160 nm/h$ for the B747-400, the final approach speed of the B737-300 is $140\, nm/h$. According to the equation (2), the initial loop amount Γ_0=594m^2/s can be obtained.

Since the duration of the diffusion phase of the wake vortex does not have an accurate value, t_1 is taken as 40.0 s according to B747 in the above figure. According to flight data from the NASA Langley Research Center, the maximum vortex bearing capacity of the B737 at low altitudes of 50-300 m is approximately 184m^2/s. The specific calculation results are shown in the following figure:

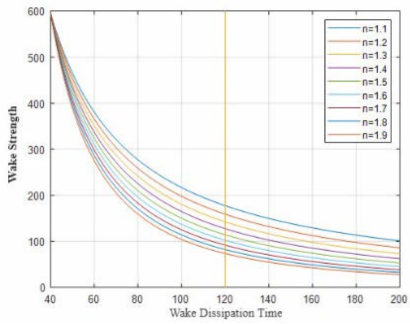

Fig. 2. Vortex dissipation time of B747

According to the formula (3), in the case of a weak dissipation rate, t = 116.13 s; in the case of a medium dissipation rate, t = 87.40 s; in the case of a strong dissipation rate, t = 74.13 s. However, with a minimum probability, the wake vortex duration of the B747 can reach 84.4 s. Therefore, under the minimum probability, according to the test (3), in the case of weak dissipation, t=245.04s; in the case of moderate dissipation, t=184.42s; in the case of strong dissipation, t=156.44s.

Through calculations, we can find that the current medium-sized machine trailing heavy machine landing separation of 2min is relatively safe. However, the minimum vortex separation of the B737-300 after the B747-400 is changed with the dissipation rate. The wake vortex will last longer with a minimum probability, so the required vortex separation is also should be increased. For relatively favorable weather conditions, we can appropriately reduce the vortex separation to increase the capacity of the airport.

5. Summary

By analyzing the characteristics of the vortex and establishing the basic model of the wake vortex, it is considered that the current aircraft enters the front wake vortex central area, which is the most harmful to the safety of the aircraft. The B747-400 is used as an example for the wake vortex intensity and the wake vortex. The attenuation was calculated to assess the safety of the currently implemented vortex separation.

However, the current phase of the vortex evolution constant is related to the specific weather conditions. There is no specific value, and some parameters in the model are difficult to determine. For example, the wake vortex dissipation rate n requires a large amount. Flight test. Due to the lack of some data in relevant domestic aspects, most of the previous examples refer to foreign data models, and there may be some errors in the calculation process. However, it can be proved that the current vortex separation still has the possibility of improvement. According to different weather conditions, establishing a dynamic vortex separation is a future development trend of increasing airport landing efficiency.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (Grant No. U1733203), Civil Aviation Administration of China’s safety capability construction Program (Grant No. TM2018-9-1/3).

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