An Influence Analysis Method of Wake Turbulence in V-open Runway Operation Mode

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Abstract. In the design of large airports in China, Beijing Daxing international airport and Chengdu Tianfu international airport have adopted V-open runways. However, there is a relative lack of operational regulations for the V-open runway at home and abroad, it is of great significance to study the mutual influence of wake of aircrafts running parallel runway and V-open runway at the same time. The formation process, change period and movement characteristics of aircraft wake are systematically studied, and the wake movement model affected by the anisotropic wind speed is established. Taking the east one and the north one runways of Chengdu Tianfu international airport as an example, the influence of the wake on each other is analyzed by using the wake movement model. The specific values of the coverage of wake dangerous area under different conditions are obtained. Calculation results show that when the runway east one and the runway west one takes independent parallel instrument approach mode, the track offset angle of go-around aircraft from the runway east one is greater than 20.3°, its wake will affect aircraft departing from runway north one.

Introduction

With the coming of 2019, as a great project of civil aviation of China, Beijing Daxing International Airport will soon be put into use. In addition, Chengdu Tianfu International Airport which also has V-open runways will be put into use in 2020. In the past designs of the airports in China, the configuration of the parallel runways is usually the first choice for the planning of multi-runway systems. However, excessive parallel runways (more than 4 runways) will reduce the efficiency of airport ground operation and lead to problems such as excessively long runway crossing or taxiing distance [1]. The V-open runway will significantly overcome these shortcomings and improve the efficiency, increase passenger handling capacity and meet the needs of growing demand for passenger and cargo transporting.

However, Chinese existing regulations on runway operation mode management only stipulate that parallel runway simultaneous instrument operation which can be divided into four modes: independent parallel instrument approach, related parallel instrument approach, independent parallel departure and isolated parallel operation [2]. In foreign countries, ICAO’s Doc9643 and DOC4444 stipulate the requirements and procedures for the four operation modes of parallel runways, but none involves the specifications of V-open runways. The relatively mature regulations of FAA on multi-runway operation are contained in ORDER JO 7110.65 and a series of amendments.

Wake turbulence considerations currently restrict the use of parallel runways less than 2500ft apart [3]. In the V-open multi-runway mode, the wake turbulence generated by taking off and landing of aircraft using parallel runways and V-open runways has mutual influence, and especially affects the takeoff and go-around of aircrafts. In China, there’s a lack of the researches for V-open runway missed approach and departure procedures and the establishments of the corresponding regulations. In order to ensure the safe and efficient, this paper will take the E1 and N1 runways of Chengdu Tianfu International Airport as an example to study the influence of wake turbulence on the go around and departure procedures.
Wake Turbulence Analysis Model

Wake Turbulence is the airflow formed in the tail of an aircraft during the flight. Although the wake turbulence in flight will not affect the flight of the aircraft itself, but it will affect the safety of the aircraft behind, such as the light or medium aircraft flying into the wake turbulence of the heavy aircraft. The danger lies in the invisibility of the wake turbulence, and the high speed airflow can cause strong turbulence and change the flight attitude of the aircraft. Therefore, the wake turbulence of aircraft during the departure, approach and go-around stages affects the operational safety of aircraft on other runways.

The Formation of the Wake

The wake in flight includes the slipstream generated by the high-speed rotation of the propeller of a propeller plane, the turbulence generated by the transverse flow on the wing surface of an airplane, the high-temperature and high-speed jet generated by the engine of a jet engine, and the tip vortex generated by the tip of an airplane wing. When entering the jet flow of a large aircraft, if it is too close, it may cause the engine of the aircraft behind to work abnormally or even stop the engine. Among the wake in flight, the tip vortex has the best impact, which is the main part of wake formed in flight of aircraft. The formation of tip vortex begins when the nose wheel of an aircraft leaves the ground at takeoff until the nose wheel is grounded at landing. There is airflow from bottom to top at the tip of the wing, thus a spiral airflow is formed, which rotates at high speed and extends backward and downward with the wingtip as the center. The eddies on the wing tips rotate in opposite directions, and a strong downdraft is formed on the inside of the two eddies, while a strong updraft is formed on the outside, thus affecting the aircraft passing behind, as shown in the picture. Inside the tip eddy current, air rotates around the center line.

The tangential velocity of rotation can reach 15-18m/s. The tangential velocity is proportional to the weight of the aircraft, and inversely proportional to wingspan, air density and flight speed. Therefore, the impact is greatest in the less speed stage of aircraft take-off, initial climb, final approach and landing.

![Figure 1. The formation of the wake.](image)

Variation of Wake

According to the characteristics of wake activity, the variation period of wake can be divided into four stages. The first is the stage of production, which is very short, only a few seconds. The second is the stable stage. For a long period of time (several minutes), the rotational velocity and shape of the wake are stable, and the laminar flow phenomena are obvious. Turbulence has little influence on the wake. The third is the weakening stage. At this stage, atmospheric turbulence has the dominant impact, and the friction effect will gradually weaken the maximum vertical velocity and the core of expanding vortices. The fourth is the stage of disappearance, all kinetic energy is depleted in friction and the wake dissipates into the random turbulence of the atmosphere.

![Figure 2. The variation of wake.](image)
The motion of the wake is a process of spinning outwards while drifting backwards. The drifting motion is mainly caused by the interaction of the downward velocity of the wake vortices rotating in opposite directions. When the wake vortex falls near the ground, the vertical motion changes to horizontal motion due to the ground, and drifts to both sides of the area below the aircraft.

When there is crosswind, the wake vortex will drift downwind while descending downward. The distance of drift is proportional to the wind speed, and the wake velocity on both sides of the wing may decrease or increase. Refer to AC90-23G of FAA and the Wake of horizontal moving part in "Pilot and Air Traffic Controller Guide to Wake Turbulence", by analyzing the crosswind statistics of 165 flight safety accidents occurred by NASA from 1988 to 1999, the crosswind speed of 1~5m·s\(^{-1}\) is the wind speed environment with multiple wake accidents, and the crosswind speed of 1~3m·s\(^{-1}\) is the most dangerous; When the crosswind speed is less than 1m·s\(^{-1}\), the lateral movement of the wake can be ignored. When the crosswind speed is greater than 3m·s\(^{-1}\), the larger crosswind will blow two tail vortices, which will dissipate rapidly\(^{[6]}\). If we limit the minimum wake velocity that has an effect to 3m/s, then the maximum survival time of the wake vortex is about 2min.

![Figure 3. The drift down of wake with crosswind.](image)

**Wake Analysis Model**

The risk to encounter a wake vortex is strongly correlated with the actual flight paths of the vortex generating aircraft and the encountering aircraft in space and time\(^{[7]}\). When the wake drops to 100-200ft from the ground, it starts to move to the two sides at a speed of 2-3kt under the ground effect\(^{[8]}\). When crosswind is present, the wake will also move downwind; In case of headwind, the wake area will be extended behind the aircraft; In the presence of tailwind, the wake will increase the rate of diffusion downwind.

1. The influence range of the wake on the runway under crosswind conditions mainly considers the following two factors:
   - Crosswind speed
   - Maximum wake lifetime

   Based on the above factors, the maximum lateral displacement distance of the trailing vortex can be calculated from the following equation \(B\)

\[
B = \frac{b_0}{2} + (V_1)t_0 
\]

\[
b_0 = \frac{\pi b}{4}
\]

In the above formulas: \(b_0\) is the initial vortex distance of two eddies of the (go-around/departure) aircraft; \(b\) is the maximum wingspan length of the (go-around/departure) aircraft; \(V_1\) is crosswind speed; \(t_0\) is the maximum lifetime of wake vortex.

2. The influence range of the wake on the runway under headwind conditions mainly considers the following three factors:
   - Headwind speed
   - Maximum wake lifetime

   The larger the wind speed is, the faster the wake dissipates. When the wind speed is greater than 5m/s, the wake dissipates faster.

   Based on the above factors, the maximum trailing vortex-backward distance can be calculated from the following equation \(C\)
\[ C = V_2 t_0 \]  

In the above formula, \( V_2 \) is headwind speed and not greater than 5m/s; \( t_0 \) is the maximum lifetime of wake vortex.

**Calculation of Missed approach point MAPt and Start of climb SOC**

The missed approach point MAPt is located at the intersection of Decision Height DH and 5.2% of the nominal descending gradient line. So:

\[ X_{MAPt} = -((DH - RDH) / 5.2\%) \]  

In the above formula: \( X_{MAPt} \) is the position of the missed approach point, \( DH \) is the decision height, \( RDH \) is the reference datum height.

\[ TAS = K \cdot IAS \]  

\[ X_{SOC} = X_{MAPt} + (TAS_{fmax} + 19 km/h) \times 18s \]  

In the above formula: \( K \) is the conversion factor, and can be found from the conversion factor table, \( IAS \) is the indicated airspeed; \( X_{SOC} \) is the position of the start of climb, \( TAS_{fmax} \) is the maximum true airspeed for the final approach of all types of aircraft.

**Chengdu Tianfu International Airport Application Instance**

**Chengdu Tianfu International Airport Runway Configuration Overview:**

Chengdu Tianfu international airport runway configuration consists of 6 runways, as shown in figure. They are a set of two widely spaced parallel runways in the west of the airport airfield, a set of two parallel runways in the southeastern part of the airfield and a set of two V-open parallel runways in the northeast of the airfield, which meet the potential four independent approach runway conditions. Among them, V-open runways are used for take-off to east and four parallel runways will be implemented the mix of take-off and landing according to different demands. Black three runways are the first phase (W1, E1, N1), gray three runways are the second phase (W2, E2, N2).

![Figure 4. Configuration diagram of Chengdu new airport runways.](image)

According to the data provided by the landlord, and elevation information of all runways are shown in the following table:

<table>
<thead>
<tr>
<th>Data type</th>
<th>Runway</th>
<th>Elevation [m]</th>
<th>Runway Length [m]</th>
<th>Runway Slope [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td></td>
<td>438</td>
<td>4000</td>
<td>0</td>
</tr>
<tr>
<td>E1</td>
<td></td>
<td>440</td>
<td>3200</td>
<td>0</td>
</tr>
<tr>
<td>N1</td>
<td></td>
<td>436</td>
<td>3800</td>
<td>0</td>
</tr>
</tbody>
</table>
Wake turbulence impact analysis of combination operation between the east runway and the north one in Tianfu international airport

With parameters of precision approach CAT II and A320 (class C), coverage of wake turbulence dangerous area can be calculated:

**Aircraft go-around/ of departure’s coverage calculation of wake turbulence dangerous area in the runway E1:**

**Aircraft going around:**
- take runway threshold as the origin and calculate the distance between MAPt and SOC:
- According to type (4), $DH = 30\text{m}$, $RDH = 15\text{m}$, so $X_{\text{MAPt}} = -288.5\text{m}$;
- According to the A320 parameters and type (5) (6), Aircraft’s $\text{IAS} = 295\text{km/h}$, $K = 1.0257$, so $\text{TAS} = 302.6\text{km/h}$; $X_{\text{SOC}} = 1319.5\text{m}$;
- Track going around which is made by aircraft landing north in the runway E1 is perpendicular to reverse extension line of the runway N1.

According to calculation in climb gradient 2.5% and Class II operational standards, when aircraft going around arrive at a tangent to the threshold of N1, the aircraft height is available:

$$(1430+3200-1319.5) \times 2.5%+30=112.8\text{m}$$

**Departure aircraft:**
- When A320 take-off run distance is 600 m, climb gradient is 3.3% and departure aircraft arrive at a tangent to the threshold of N1, the aircraft height is available:

$$(1430+3200-600) \times 3.3%=133.0\text{m};$$
- Because the departure aircraft height is higher, drifting distance of wake turbulence impacted by ground effect or crosswind from the west to the east is further and dangerous area of wake turbulence caused by departure aircraft affects runway N1 deeper. So dangerous area of wake turbulence caused by departure aircraft will be final.

**Coverage calculation of wake turbulence dangerous area:**
- $b$ takes 65 m, which is the largest wingspan 4E airfield index can hold; The largest survival time limit is 2 min, so $t_0 = 120\text{s}$; The maximum crosswind speed $V_1 = 3\text{m/s}$;
- According to type (1) (2), $B = 411.1\text{m}$. Therefore, the biggest influence range of wake turbulence is $71.1\text{m}$ from the runway threshold to the east.
- Taxi distance of take-off aircraft from runway N1 is at least 600 m from the runway threshold, so the wake turbulence caused by aircraft going around/departure aircraft does not affect aircraft to take off from runway N1.

**Coverage calculation of wake turbulence dangerous area from runway N1:**
- According to type (1), when $V_2 = 5\text{m/s}$, $t_0 = 120\text{s}$, the maximum distance that wake turbulence go to west is available: $5\text{m/s} \times 120\text{s} = 600\text{m}$;
- When climb gradient of departure aircraft from runway E1 is 3.3%, height of climbing to a tangent to the threshold of N1 is at least 51 m.
- Track is over wake turbulence when aircraft going around/departure aircraft fly over runway N1. So, the wake turbulence caused by departure aircraft from runway N1 does not affect aircraft to go around from runway E1.

**Coverage calculation of the north offset go-around aircraft wake turbulence dangerous area on the runway E1:**
- Runway E1 and W1 adopt independent parallel instrument approach mode. According to the "management regulations on parallel runway simultaneous instrument operation", the diffusion angle between the go-around track of one runway and the go-around track of the adjacent runway isn’t less than 30°. It can be known the runway E1 go-around track can be offset 0° to 30° to the right.
- In this mode runway N1 go-around heading to east when offset at 15°. track of going around and runway N1 overlapping, intersection in the runway to east runway entrance 43.2 m when offset at 20.3°, intersection in the runway to the east runway entrance 189.0 m when offset at 25°, intersection in the runway to the east runway entrance 326.8 m
Table 2. Wake turbulence dangerous areas with different offset angle.

<table>
<thead>
<tr>
<th>Offset Angle [°]</th>
<th>0</th>
<th>15</th>
<th>20.3</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersection [m]</td>
<td>-340</td>
<td>43.2</td>
<td>189.0</td>
<td>326.8</td>
<td>485.6</td>
</tr>
<tr>
<td>Maximum lateral displacement points of wake [m]</td>
<td>71.1</td>
<td>454.3</td>
<td>600.1</td>
<td>737.9</td>
<td>896.7</td>
</tr>
</tbody>
</table>

Known from the above analysis, when offset angle of track of runway E1 going around to north is less than 20.3°, wake over the runway E1 does not affect the N1 aircraft which will take off, when the offset angle is greater than 20.3° and less than 30° wake over the runway N1 will affect runway N1 take-off aircraft.

Conclusion

In this paper, the motion model of wake under the influence of anisotropic wind speed is established by analyzing the formation, drifting and dissipation of aircraft wake as well as the movement law of aircraft wake. Taking the east one and north one runways of Chengdu Tianfu international airport as an example, the coverage areas of the departure and go-around aircraft wake danger areas of the two runways were studied. The results show that in the approach mode of independent parallel instrument, there exists the possibility that the wake of the parallel runway offsetting go-around aircraft may affect the aircraft taking off from the V-open runway.

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References


