Determining the approach speed envelope of carrier aircraft

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Abstract: Many factors, such as deck motion and air wave, influence the determination of the approach speed which has an important effect on landing safety. Until recently, there are no design criteria about approach speed of carrier aircraft in the current standards and available publications. Therefore, the requirements of stall margin, longitudinal acceleration ability, altitude correction and field-of-view on approach speed were researched. Based on the flight dynamics model, the flight simulations were conducted to study the effect of the response time of engine, wave off requirements, elevator efficiency and deflection rate on the approach speed. The results presented that the approach longitudinal acceleration and altitude correction ability had crucial influence on the approach speed envelope of the aircraft. The limitations of the control requirements, field-of-view requirements and gear were also given through the simulation and analysis. Based on the above results, the approach speed envelope were determined.

Key words: carrier aircraft; approach speed; altitude correction; handling quality; landing safety

1 Introduction

The statistical results of US Navy on the carrier aircraft landing accidents show that the approach speed is a key factor impacting on landing accident ratio. When the speed is too slow, the attack angle of the aircraft is too large nearly to the critical value, which will impact aircraft control and also have adverse effects on the wind and other disturbance factors. Besides, it will lead to wave off if the pilot cannot see the landing runway starting point when the aircraft is approaching to the carrier. When the speed is too fast, the reaction time remaining for pilot is so short as to increase the probability of the accidents together with many other disturbing factors in the landing end. If the approach speed is too fast, the design requirements for the landing gear and arrest system are difficult to be satisfied.

The approach speed impacts on the safety flight directly, but there are no design criteria about approach speed of carrier aircraft in the current standards and available publications. In this paper, the approach speed envelope is designed by simulation according to the influencing factors of the approach speed of carrier aircraft.

2 Approach dynamics model of carrier aircraft

The dynamics model for landing of carrier aircraft is different from the land-based aircraft when it flights along the $-4\degree \sim -3\degree$ glide slope offered by aided landing system. The 6 degree of freedom (DOF) dynamics model of the aircraft is given in Eq.(1)–Eq.(3)\(^1\).

\[
\begin{align*}
\dot{u} &= r v - qw - g \sin \theta + \frac{1}{m} (X + T_x) \\
\dot{v} &= p w - ru + g \sin \phi \cos \theta + \frac{1}{m} Y \\
\dot{w} &= q u - pv + g \cos \phi \cos \theta + \frac{1}{m} (Z + T_z) \\
\dot{p} &= (c_r + c_r p) q + c_s L + c_s N \\
q &= c_s p r - c_s (p^2 - r^2) + c_r M \\
r &= (c_r - c_r) q + c_o L + c_o N \\
\phi &= p + \tan \theta (q \sin \phi + r \cos \phi) \\
\theta &= q \cos \phi - r \sin \phi \\
\psi &= (q \sin \phi + r \cos \phi) / \cos \theta 
\end{align*}
\]

Received 11 July 2012
where, \[ c_1 = \frac{(I_x - I_y)I_y - I_z}{I}; \quad c_2 = \frac{(I_y - I_z)I_z - I_x}{I}; \quad c_3 = \frac{(I_z - I_x)I_x - I_y}{I}; \]

are the rotation inertias corresponded to \( x, y, z \) body axis; \( I_x, I_y, I_z \) are the products of inertias; \( u, v, w \) are the speed components along the three \( x, y, z \) body axis directions; \( p, q, r \) are the angular velocities of rotation along the \( x, y, z \) body axis; \( X, Y, Z \) are the components of the aerodynamic along the \( x, y, z \) body axis; \( T_x, T_y, T_z \) are the components of the engine thrust along the \( x, y, z \) body axis; \( L, M, N \) are the roll moment, pitching moment and yawing moment of the aerodynamic, respectively. Fig.1 shows the schematic diagram of simulation model.

3) Altitude correction criterion. Altitude correction requests illuminate the ability to correct the altitude error of the aircraft. A 15 m altitude error must be corrected in 5 s while using no more than one half of the maximum normal acceleration capability.

4) Flying qualities criterion. The flight qualities must satisfy the interrelated requests of GJB 185—86 while at \( V_{\text{mmin}} \).

5) Field-of-view criterion. The slowest acceptable approach speed must provide adequate field of view, so that with the aircraft at an altitude of 183 m in level flight and with the pilot’s eyes at the design eye position, the waterline at the stern of the carrier must be visible upon intersecting a 4° optical glide slope in order to ensure the pilot can maintain the glide slope and well line up.

4 Determining the approach speed envelope

4.1 The limitations of field of view

The source of optical slope locates at 152 m forward of the ramp, 19.8 m above the waterline. According to the field-of-view criterion, with the aircraft at an altitude of 183 m in level flight and with the pilot’s eyes at the design eye position, the waterline at the stern of the carrier must be visible. Fig.2 shows the approach field of view schematic diagram of carrier aircraft.

Fig.1 Model schematic diagram

Fig.2 Approach field of view schematic diagram of carrier aircraft

With reference to Fig.2, the angle between line of vision and 4° glide slope is 0.8°. From the geometry relationship, the line of vision is determined by \( \alpha \). Measured from the body \( x \) axis, the angle of the line of vision is \( \alpha + 4.8° \). When the maximum depression angle \( \theta_m \) is determined, the maximum permissible attack angle is \( \alpha_{\text{m}} = \theta_m - 4.8° \). The maximum depression angle of the carrier aircraft is \( 20° \), and the maximum permissible attack angle is \( 15.2° \). The speed of straight and level flight can be got from Eq. (4).
The wave off often occurs in landing. The bad landing environment, flight technical error or beyond the safety landing state may result in wave off. The capability of longitudinal acceleration is the key factor for wave off of carrier aircraft. When carrier aircraft is approaching at the minimum approach speed, it is demanded that the level state of zero track angle and longitudinal accelerative effect must be enough from the accelerator action to the military thrust position; the acceleration must be 1.5 m/s² at least in 2.5 s.

Fig.3 is the engine response sketch map. \( \tau \) is the response time from trim thrust \( P_t \) to military thrust \( P_m \). According to the approach dynamics model in section 2, the effect on the longitudinal accelerative performance is given in different response time through adjusting \( \tau \). Fig.4 shows that the engine response time affects the approach speed distinctly and when \( \tau < 2.5 \, \text{s} \), 175 km/h < \( V_m \) < 235 km/h or \( \tau = 3 \, \text{s} \), 175 km/h < \( V_m \) < 195 km/h, the accelerative performance satisfies the requirement. However, when \( \tau > 2.5 \, \text{s} \), the maximum limit of \( V_m \) decreases quickly; when \( \tau = 3 \, \text{s} \), the scope of the limitation is too narrow. So the engine response time is not permitted to exceed 2.5 s.

\[
V = \sqrt{\frac{2(mg - P \sin(\alpha + \varphi))}{C_i S \rho}}
\]  \hspace{1cm} (4)

where, \( m \) is mass of aircraft; \( g \) is the gravitational acceleration; \( P \) is engine thrust; \( \alpha \) is attack angle; \( \varphi \) is engine setting angle; \( C_i \) is lift coefficient; \( S \) is wing area; \( \rho \) is atmospheric density.

For approach configuration of an aircraft, the maximum lift coefficient is 2.04; weight of aircraft is 21 000 kg and wing area is 70 m². The 15.2° is already over the critical attack angle. From Eq.(4), the stall speed of the approach configuration is 41.5 m/s. So it can meet the requirement of field-of-view criterion as long as the aircraft is not in stall during approaching.

### 4.2 The limitations of engine response time on approach speed

According to the altitude correction criteria, a 15 m altitude error must be corrected in 5 s while using no more than one half of the maximum normal acceleration capability. Based on the approach dynamics model, the altitude correct ability is verified through the simulation with different elevator efficiencies and deflection rates. The AOA control law is adopted to prevent the stall. Fig.5 presents the control law model.

Fig.6 presents the simulation results of the altitude correction based on different elevator efficiencies and deflection rates with no throttle changes. Fig.6 shows that with the increase of the speed and elevator efficiency, a 15 m altitude error can be corrected in shorter time. The deflection rate has small impact on the altitude correct capability except that the speed is slower than 190 km/h. When the speed is faster than 190 km/h, a 15 m altitude error can be corrected in longer time due to a lower deflection rate and control law. With the deflection rate increasing, the aircraft does not have the altitude correction ability. Fig.6 also shows that if the approach speed is faster than 190 km/h, a 15 m altitude error can be corrected in 5 s while using no more than one half of the maximum normal acceleration capability; otherwise, the altitude corrected capability cannot satisfy the re-
requirement of the specification.

Fig. 6 The effect of elevator efficiency and deflection rate on approach speed

4.4 Flying qualities criterion on the limitations of approach speed

Thanks to the development of the modern control system, when the flying qualities of the uncontrolled aircraft, which can not satisfy the standards, can be relaxed in aircraft design. The corresponding items can be adjusted through the control system. If the flight control systems fail, the handling quality can be degraded. The carrier aircraft must land on the carrier safely, even on the flight control system malfunction. The aircraft responds need to meet the landing requirements to avoid the danger, which demands the uncontrolled aircraft has good quality.

Fig. 7–Fig. 9 present the natural characteristics calculation results of an aircraft. The figures show that the short-period characteristics meet the requirements of the standards; the long-period characteristics only satisfy the level 2 at low speeds. When the speed increases, damping ratio enhances. From the results, the aircraft should improve the approach speed to ensure the better quality characteristics when the control system fails.

Fig. 7 Long-period damping ratio of an aircraft (approach configuration)

4.5 Stall speed margin

Stall speed margin is a critical parameter used by carrier aircraft designers in determining approach speed. When the carrier-based propeller-driven aircraft approaches straight-deck carriers using a “flat-paddles” approach technique, the specifications specify the design approach speed to be 1.05–1.10 times the stall speed. Subsequently, the jet aircraft indicates that the minimum approach speed must be 1.1 times higher than the stall speed.

According to the requirements of the stall speed margin, the approach speed of a carrier aircraft is 1.1 times higher than the power-on stall speed $V_{\text{op}}$. The power-on stall speed is 168 km/h depending on the aerodynamic characteristics of the carrier aircraft. So the approach speed $V_p$ is higher than 185 km/h.

4.6 Other limitations

4.6.1 Gear load limitation

Due to the limitations of gear load and arrest system, the landing speed is not too high. Ref. [5] presented the maximum sinking speed calculation formula

$$V_c = 0.039V_{\text{bn}} + 3.1$$

where, $V_{\text{bn}}$ is the average engaging speed,
$V_{ma} = 1.05V_{ma}$. Then we can get

$$V_e = 0.040 \times 95V_{ma} + 3.1 = V_{ma} \sin(4/57.3)$$ (6)

From Eq. (6), we can get

$$V_{max} = 387 \text{ km/h}$$ (7)

where, $V_{max}$ is the maximum approach speed of the landing gear load restrictions at which the deck motion is excluded.

Considering the moderate sea condition, the additional sinking speed caused by the deck motion is 1.5 m/s; here $V_{max}$ is 200 km/h.

### 4.6.2 Arrest system limitation

For different landing weights, the engaging speed is not higher than the limited speed. Table 1 presents the limited engaging speed of the arrest system MK7-1, MK7-2 and MK7-3, where the aircraft mass is 21 000 kg. Table 1 shows the limited engaging speed of the MK7-3 is 252 km/h (8).

<table>
<thead>
<tr>
<th>Arrest system</th>
<th>Limited engaging speed (km·h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK7-1</td>
<td>204</td>
</tr>
<tr>
<td>MK7-2</td>
<td>230</td>
</tr>
<tr>
<td>MK7-3</td>
<td>252</td>
</tr>
</tbody>
</table>

### 4.7 The determination of approach speed envelope

Table 2 presents the limitations of the approach speed of a carrier aircraft. It shows that the maximum approach speed is limited by the longitudinal acceleration ability, landing gear load and the arrest system capacity. Considering the moderate sea condition, when the engine response time is 2.5 s, the maximum approach speed is 200 km/h, which is restricted by landing gear. The maximum approach speed is 230 km/h limited by the longitudinal acceleration ability without considering the deck motion. The minimum approach speed is 195 km/h, which is restricted by altitude correction ability.

Considering moderate sea condition, the approach speed envelope of the aircraft is

$$195 \text{ km/h} < V_{ma} < 200 \text{ km/h}$$ (8)

Without considering the deck motion, the approach speed envelope of the aircraft is

$$195 \text{ km/h} < V_{ma} < 230 \text{ km/h}$$ (9)

The sea condition has the important influence on the approach speed envelope. The sea condition is more wild, and approach envelope is narrow. The flying qualities limitations on the approach speed are not presented in Table 2, which are mainly reflected in the control system failure. The requirements of the flying qualities are different for different failure states, and the approach restrictions are determined based on the specific malfunctions.

### 5 Conclusions

The engine response time and the elevator efficiency have important influence on the approach speed envelope. With faster engine response, the maximum approach speed is higher; with higher elevator efficiency, the minimum approach is lower. A series of restrictions of landing gear can be given according to different sea conditions. The approach speed envelope is narrow for an aircraft only considering the moderate sea condition. It is not practical without considering the sea condition.

### References


