Aerodynamics & Flight Mechanics (AMV)

LESSON 4:
TAKE-OFF AND LANDING PERFORMANCES

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INTRODUCTION

Airplane flight mechanics can be divided into 3 broad areas:

*Big motions*:

- trajectory analysis (performances)

  so far all acceleration = 0: static performance

  **study of dynamic performance: take-off, landing runs**...

- stability and control

*Small motions*:

- aeroelasticity
INTRODUCTION

• Take-off performance: ground roll (with all wheels & only main gear) + air path (transition + stabilized straight ascent)

• what is the running length along the ground required by an airplane, starting from zero velocity, to gain flight speed and lift from the ground? → this length = ground roll or lift-off (LO or LOF subscript) distance, $x_{\text{LOF}}$

• Hypothesis: symmetric aircraft, longitudinal movement only, thrust can often be considered constant and (generally) maximum or close to its maximum value
Total take-off distance (from the release of brakes until reaching a defined height and speed defined by the Federal Aviation Requirements FAR) = $x_{LOF} + \text{distance to clear a 35-ft height (for jet-powered civilian transport) or a 50-ft height (for all other airplanes)}$
Hypothesis: Thrust parallel to the runway axis, horizontal runway

→ $N_1$ at $V_R$ ?

→ $N_1 + N_2$ at $V_{LOF}$ ?

[Gómez, 2012]
1. GROUND ROLL DURING TAKE-OFF

a. With all wheels on the ground

\[ ma_1 = F = T - \mu W - \left( \frac{1}{2} \rho S V^2 (C_D - \mu C_L) \right) \]

With constant pitch angle = constant angle of attack \( \rightarrow \) constant \( C_D, C_L \)

b. With main landing gear on the ground

\[ ma_2 = F = T - \mu W - \left( \frac{1}{2} \rho S V^2 (C_D(\alpha) - \mu C_L(\alpha)) \right) \]

With increasing pitch angle = increasing \( \alpha \) \( \rightarrow \) non-constant \( C_D, C_L \)

c. Distance and time spent in ground rolling

Could be obtained by integration using that \( dx = Vdt = \frac{Vdv}{a} \)

\[ x_{LOF} = \int_0^{x_{LOF}} dx = \int_0^{V_{LOF}} \frac{Vdv}{a} : \text{not easy for non-constant} \; C_D, C_L \]
1. GROUND ROLL DURING TAKE-OFF

Remark: Ground effect

Wing tip vortices diminished because of the interaction with the ground

→ downwash reduced

→ induced drag reduced

→ $C_D$ and $C_L$ different than the ones in the air

• Ekranoplan

(see on Atenea “Caspian Sea Monster Ekranoplan Flight Video”)
Remark: Ground effect

Tendency for an airplane to “float” above the ground near the instant of landing.

Reduced drag accounted for $\Phi$: $C_D = C_{D0} + \phi \frac{C_L^2}{\pi A e}$

Approximate expression for based on aerodynamic theory:

$$\phi = \frac{(16 h / b)^2}{1 + (16 h / b)^2}$$

[McCormick, 1979]

where $h$: height of the wing above the ground

and $b$: wingspan
1. GROUND ROLL DURING TAKE-OFF

Ground roll can also and more easily be obtained *approximatively* using a series of hypothesis:

→ suppose aircraft has a uniformly accelerated movement driven by a constant averaged force:

\[
F_{LO} = T - [D + \mu(W - L)]_{av} = T - [D + \mu(W - L)]_{0.7V_{LOF}}
\]

→ average force set equal to its instantaneous value at a velocity equal to 0.7\(V_{LOF}\) [Shevell, 1983]

→ typically, suppose \(V_{LOF}\) is stall speed at take-off configuration + 10% security margin (ex. FAR 25 requirements):

\[
V_{LOF} = 1.1V_S = 1.1\sqrt{\frac{2W}{\rho S C_{L_{max}}}}
\]
1. GROUND ROLL DURING TAKE-OFF

Typical variation of forces acting on an airplane during take-off:

Under these hypothesis:

\[ x_{LO} = \frac{V_{LOF}^2 W}{2gF_{LO}} \]

and

\[ t_{LO} = \frac{V_{LOF} W}{gF_{LO}} = \sqrt{\frac{2x_{LO} W}{gF_{LO}}} \]

Proof: see exercise 1 (Atenea)

[Anderson, 2005]
1. GROUND ROLL DURING TAKE-OFF

Estimated ground roll lift-off distance:

\[
x_{LO} = \frac{V_{LOF}^2 W}{2gF_{LO,0.7V_{LOF}}} = \frac{V_{LOF}^2 W}{2g\left(T - [D + \mu(W - L)]0.7V_{LOF}\right)}
\]

You may sometimes consider that \( T \gg [D + \mu(W - L)] \)
and thus simplify the ground roll distance as

\[
x_{LO} = \frac{V_{LOF}^2 W}{2gT}
\]

- \( x_{LO} \) very sensitive to weight of airplane, varying directly as \( W^2 \)
- \( V_{LOF}^2 \propto 1/\rho \), and (recall lecture #3) \( T \propto \rho^x \rightarrow x_{LO} \propto \frac{1}{\rho^{1+x}} \)
- \( x_{LO} \) decreased by increasing: wing area, \( C_{L,\text{max}} \), and thrust
- \( \mu \) usually varies from 0.02 (smooth paved surface) to 0.10 (grass field)
2. TAKE-OFF

Hypothesis: For $V_{\text{LOF}}$ calculation, small pitch angle $\rightarrow$ vertical component of Thrust $<<$ other forces

But for Minimum Unstick velocity ($V_{\text{MU}}$): high pitch angle $\rightarrow$ vertical component of Thrust similar to other forces $\rightarrow$ high pitch angle determines $V_{\text{MU}}$ (see on Atenea video of Airbus A380 Tail Strike Test with “the other” Fernando Alonso)

(Suppose Thrust along body axis and V parallel to runway)
3. AIR PATH DURING TAKE-OFF

Horizontal distance during air path obtained adding distances from:

a. Transition (circular trajectory)  
   see equations studied in previous flight mechanics lectures

b. Stabilized straight ascent
4. LANDING PERFORMANCES

Two main phases:

1. in the air: final approach & rounding until touchdown

2. ground roll: with only main gear & with all wheels

Again, distances can be obtained: exactly by integration or approximatively using a series of hypothesis
4. LANDING PERFORMANCES

Same force diagram during ground roll as take-off but instantaneous acceleration is negative

- thrust: $T \sim 0$ or negative (thrust reverser: 40-60% of max $T$)
  (see video on Atenea “C-17 Globemaster III Reverse Thrust Stunt – Short”)

- equation of motion

$$\begin{align*}
\left[-T\right] - D - \mu(W - L) &= m \frac{dV}{dt} \\
\end{align*}$$

$\Rightarrow$ Suppose aircraft has a uniformly accelerated movement driven by a constant force set equal to its instantaneous value at a velocity equal to $0.7V_{TD}$: $F_L = -\left[D + \mu(W - L)\right]_{av} = -\left[D + \mu(W - L)\right]_{0.7V_{TD}}$

$\Rightarrow$ Typically, suppose $V_{TD}$ is stall speed at landing configuration + 15% security margin: $V_{TD} = 1.15V_{stall} = 1.15 \sqrt{\frac{2W}{\rho S C_{L,max}}}$
4. LANDING PERFORMANCES

Under these hypothesis: (with convention that $F_L < 0$)

$$x_L = - \frac{V_{TD}^2 W}{2gF_L} \quad \text{and} \quad t_L = - \frac{V_{TD} W}{gF_L} = \sqrt{\frac{2x_L W}{g(-F_L)}}$$

we obtain the estimated landing ground roll distance between touchdown and complete stop:

$$x_L = \frac{V_{TD}^2 W}{2g[D + \mu(W - L)]_{0.7V_{TD}}}$$

with:

$$V_{TD} = 1.15 \sqrt{\frac{2W}{\rho S C_{L,max}}}$$

- pilot applies brakes: $\mu \sim 0.4$ for paved surface
- spoilers “break” lift and increase drag
- modern jet transports use thrust reversal during the landing ground roll
REFERENCES


• *Mecánica del vuelo*, M.A. Gómez Tierno, M. Pérez Cortés, C. Puentes Márquez, 2ª Edición, Garceta, 2012
