Lecture 1: Introduction to Flight Dynamics, Stability & Control

*Or appreciating the basic terms and concepts*
1.0 Course Info

- Instructor: Associate Professor Gerard Leng
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1.1 Course requirements

• Background (Basic engineering courses ~ stage 1&2 )
  – Dynamics
  – Calculus
  – Computer programming (C/C++)
  – Feedback & Control
  – Matlab (optional)

• Open Book Exam (80%), CA (20%)
1.2 Recommended References


• Louis V. Schmidt, “Introduction to Aircraft Flight Dynamics”, AIAA, 1997
1.3 Industrial standards

- FAR Part 23: Airworthiness standards: Normal, utility, acrobatic, and commuter category.

- FAR Part 25: Airworthiness standards: Transport category airplanes

- MIL-F-8785C: Flying qualities of piloted airplanes. (pre 1996)

- MIL-STD-1797B: Flying qualities of piloted aircraft (post 1996)

- MIL-F-9490D: Flight control systems, design, installation and testing of piloted aircraft, General specifications for.

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1.4 Training programme

1. Basic aerodynamic terms and concepts

2. The flight environment

3. Static longitudinal & lateral stability

4. Equations of motion

5. Dynamic stability

6. Design of flight control systems

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2.0 Basic aerodynamic terms and concepts

Mission Profile

Propulsion

Aerodynamics

Structures

Flight Dynamics & Control

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2.1 Angle of attack (AOA) $\alpha$ and sideslip angle $\beta$

AOA is the angle between the direction of the airflow and the wings.
Sideslip angle is the angle between the velocity vector and the aircraft plane of symmetry.

By convention sideslip to the right is positive.

Typically one tries to fly with zero sideslip.

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2.2 : Definition of lift & drag coefficients $C_L$ and $C_D$

Aerodynamic forces are typically expressed as

\[ L = \frac{1}{2} \rho V^2 S C_L \]

Similarly for the drag coefficient \( D = \frac{1}{2} \rho V^2 S C_D \)
Question: How does the lift coefficient vary with AOA?

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Question: How large are lift forces for a typical combat aircraft?

From Jane’s all the World’s aircraft

F16C (F100 PW engine)

Weight empty = 8,433 kg

Takeoff Weight = 12,138 kg
(2 AAM, no tanks)

So what’s the lift force?
Question:

How does combat aircraft weight vary with a typical mission?

What about a civilian aircraft?
Weight variation of an Airbus A380-800

Empty : 277,000 kg
Max Takeoff : 560,000 kg
Fuel Capacity : 260,900 kg
Max Payload : 84,000 kg
Question: How does the operational altitude and airspeed vary?
Question: So what are typical values for the lift coefficients?

F16, 1g sustained (level flight) at 700 kts, 50 kft

air density (15.2 km) =

airspeed =

weight (2 AAM 50% fuel) = 10 659 kg

wing area = 27.87 m²

Hence $C_L = \frac{W}{\frac{1}{2} \rho V^2 S}$

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Question : Is $C_L$ constant throughout flight?

Example : F16 flap schedule
2.3 : Describing wing shapes

b : span

c : mean aerodynamic chord

S : surface area

\[ \Lambda = \frac{b^2}{S} \]

F16

\[
\begin{align*}
b &= 9.14 \text{ m} \\
S &= 27.87 \text{ m}^2 \\
\Lambda &= \text{(to be calculated)}
\end{align*}
\]
What’s the aspect ratio for the Airbus A380-800?

Wing span : 79.80 m
Wing area : 845.0 m²

\[ \Lambda = \]
Extreme example - Scaled Composites Model 311 Virgin Atlantic GlobalFlyer

2005 28/2 – 3/3, fastest, nonstop, unrefueled solo circumnavigation

Wing span : 34.75 m
Wing area : 37.16 m²

\[ \Lambda = \]
2.4 The mean aerodynamic chord

The mean aerodynamic chord is defined by:

\[ c_{mac} = \frac{\int_{-b/2}^{b/2} c(y)^2 \, dy}{S} \]

The span-wise location of the mean aerodynamic chord is at:

\[ y_{mac} = \frac{\int_{0}^{b/2} c(y) y \, dy}{S/2} \]
Homework: Linear taper wings

Show

1. For the right wing \( c(y) = c_0 \left[ 1 - 2 \left( 1 - \lambda \right) \left( y/b \right) \right] \)

2. \( c_{\text{mac}} = \frac{2}{3} c_0 \frac{1 + \lambda + \lambda^2}{1 + \lambda} \)

3. \( y_{\text{mac}} = \frac{b}{6} \frac{1 + 2\lambda}{1 + \lambda} \)

4. \( c(y_{\text{mac}}) = c_{\text{mac}} \)

Root chord \( c_0 \)    Tip chord \( c_1 \)    Taper ratio \( \lambda = \frac{c_1}{c_0} \)

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2.5 Concept of wing loading

A measure of force distribution on an aircraft

\[
\text{Wing loading} = \frac{\text{Lift force}}{\text{Wing area}}
\]

For level flight,

\[
\text{lift} = \text{weight}
\]

hence

\[
\text{wing loading} = \text{W/S}
\]

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Question: What is the wing loading for typical combat aircraft?

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>b (m)</th>
<th>S (m²)</th>
<th>AR</th>
<th>W/S (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F104</td>
<td>6.68</td>
<td>18.2</td>
<td>2.45</td>
<td>4856</td>
</tr>
<tr>
<td>MIG 21</td>
<td>7.15</td>
<td>23.2</td>
<td>2.2</td>
<td>3463</td>
</tr>
<tr>
<td>X31</td>
<td>7.26</td>
<td>21.02</td>
<td>2.5</td>
<td>2954</td>
</tr>
<tr>
<td>F5</td>
<td>7.7</td>
<td>15.79</td>
<td>3.75</td>
<td>3989</td>
</tr>
<tr>
<td>Gripen</td>
<td>8</td>
<td>28.4</td>
<td>1.09</td>
<td>2761</td>
</tr>
<tr>
<td>Mirage III</td>
<td>8.22</td>
<td>34.85</td>
<td>1.94</td>
<td>2220</td>
</tr>
<tr>
<td>Kfir</td>
<td>8.22</td>
<td>34.8</td>
<td>1.94</td>
<td>4647</td>
</tr>
<tr>
<td>Jaguar</td>
<td>8.49</td>
<td>24</td>
<td>3</td>
<td>4263</td>
</tr>
<tr>
<td>Tornado</td>
<td>8.6</td>
<td>42.3</td>
<td>1.75</td>
<td>6305</td>
</tr>
<tr>
<td>Mirage 2000</td>
<td>9.13</td>
<td>41</td>
<td>2.03</td>
<td>4063</td>
</tr>
<tr>
<td>F16</td>
<td>9.14</td>
<td>27.87</td>
<td>3</td>
<td>3449</td>
</tr>
<tr>
<td>EFA</td>
<td>10.5</td>
<td>50</td>
<td>2.205</td>
<td>3332</td>
</tr>
<tr>
<td>Viggen</td>
<td>10.6</td>
<td>46</td>
<td>2.44</td>
<td>3622</td>
</tr>
<tr>
<td>Rafale</td>
<td>11.2</td>
<td>47</td>
<td>2.67</td>
<td>2919</td>
</tr>
<tr>
<td>F18</td>
<td>11.43</td>
<td>37.2</td>
<td>3.52</td>
<td>3250</td>
</tr>
<tr>
<td>F14</td>
<td>11.72</td>
<td>66.3</td>
<td>2.07</td>
<td>3847</td>
</tr>
<tr>
<td>F4</td>
<td>11.8</td>
<td>49.26</td>
<td>2.82</td>
<td>3545</td>
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<tr>
<td>F15</td>
<td>13.04</td>
<td>59.3</td>
<td>2.88</td>
<td>3556</td>
</tr>
<tr>
<td>MIG 25</td>
<td>14</td>
<td>56</td>
<td>3.07</td>
<td>4764</td>
</tr>
</tbody>
</table>

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Figure 2.1
Moral

Large W/S  \iff  less sensitive to gust

Small W/S  \iff  better manoeuvrability

Question: Why?
## Wing loading: a comparison

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Mass (kg)</th>
<th>Wing Area (m²)</th>
<th>W/S (N/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A380</td>
<td>560 000</td>
<td>845</td>
<td></td>
</tr>
<tr>
<td>F15</td>
<td>21 500</td>
<td>59.3</td>
<td></td>
</tr>
<tr>
<td>F16</td>
<td>9 800</td>
<td>27.87</td>
<td></td>
</tr>
<tr>
<td>GlobalFlyer</td>
<td>10 024</td>
<td>37.16</td>
<td></td>
</tr>
</tbody>
</table>

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3.0 Axis System

1: For flight dynamics and control the axis system or reference frame is *fixed* to the flight vehicle.

2: The *convention* for flight dynamics is to place the origin at the centre of mass of the aircraft with

   I) The positive x axis points towards the nose
   II) The positive y axis points towards the right wing
   III) The positive z axis points *downwards*.

NB: Aerodynamics, propulsion & structures use different conventions
Figure 3.1: Axis system
3.1 Describing Aircraft Motion

The aircraft can rotate about the 3 axes

<table>
<thead>
<tr>
<th>Term</th>
<th>Physical description</th>
<th>rotation axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>roll</td>
<td>wings up/down</td>
<td>X</td>
</tr>
<tr>
<td>pitch</td>
<td>nose up/down</td>
<td>Y</td>
</tr>
<tr>
<td>yaw</td>
<td>nose right/left</td>
<td>Z</td>
</tr>
</tbody>
</table>

Positive direction of rotation determined by right hand rule
3.2 Means of controlling roll, pitch & yaw

Present aircraft use control surfaces to generate the aerodynamic forces/moments for roll, pitch and yaw

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Question: What’s downwash?

Downwash refers to the effect airflow coming off from the wing has on the tail.
3.3 Nomenclature & symbols

\( \alpha \) : angle of attack (AOA)
\( \beta \) : sideslip angle
\( \delta a \) : aileron deflection
\( \delta e \) : elevator deflection
\( \delta r \) : rudder deflection
\( \rho \) : air density
\( \phi, \theta, \psi \) : roll, pitch and yaw angles

\( l.m.n \) : roll, pitch & yaw moments
\( p,q,r, \) : roll, pitch and yaw angular rates
\( u,v,w \) : velocity X,Y & Z components