Experimental Aerodynamics

Lecture 4:
Delta wing experiments

G. Dimitriadis
Introduction

- In this course we will demonstrate the use of several different experimental aerodynamic methodologies.
- The particular application will be the aerodynamics of Delta wings at low airspeeds.
- Delta wings are of particular interest because of their lift generation mechanism.
Delta wing history

• Until the 1930s the vast majority of aircraft featured rectangular, trapezoidal or elliptical wings.
• Delta wings started being studied in the 1930s by Alexander Lippisch in Germany.
• Lippisch wanted to create tail-less aircraft, and Delta wings were one of the solutions he proposed.
Delta Lippisch DM-1

Designed as an interceptor jet but never produced. The photos show a glider prototype version.
High speed flight

- After the war, the potential of Delta wings for supersonic flight was recognized both in the US and the USSR.

MiG-21

Convair XF-92
Low speed performance

• Although Delta wings are designed for high speeds, they still have to take off and land at small airspeeds.
• It is important to determine the aerodynamic forces acting on Delta wings at low speed.
• The lift generated by such wings are low speeds can be split into two contributions:
  – Potential flow lift
  – Vortex lift
Delta wing geometry

Wing surface: \( S = \frac{cb}{2} \)

Aspect ratio: \( AR = \frac{2b}{c} \)

Sweep angle: \( \tan \Lambda = \frac{b}{2c} = \frac{AR}{4} \)
Potential flow lift

- Slender wing theory
- The wind is discretized into transverse segments.
- The flow around each segment is modeled as a 2D flow past a flat plate perpendicular to the free stream
Slender wing theory

- The problem of calculating the flow around the wing becomes equivalent to calculating the flow around each 2D segment.

Model the flow using a continuous Vorticity distribution
Slender wing theory 2

• It can be shown that the potential of the flow on either side of plate is given by

\[ \Phi(x, y, 0^\pm) = \pm U_\infty \sin \alpha \sqrt{\left( \frac{b(x)}{2} \right)^2 - y^2} \]

• The chordwise component of velocity is given by

\[ u(x, y, 0^\pm) = \frac{\partial \Phi(x, y, 0^\pm)}{\partial x} = \pm U_\infty \sin \alpha \frac{b(x)}{2 \sqrt{b(x)^2 - 4y^2}} \frac{\partial b}{\partial x} \]
Pressure

- The pressure difference between the two sides of the wing can be obtained from Bernoulli’s equation

\[ p_t = p(x, y, 0^\pm) + \frac{1}{2} \rho (U_\infty + u(x, y, 0^\pm) + v(x, y, 0^\pm) + w(x, y, 0^\pm))^2 \]

- Where \( p_t \) is the total pressure and \( p \) is the static pressure. Assuming that \( u, v \) and \( w \) are small and linearizing gives

\[ p_t = p(x, y, 0^\pm) + \rho U_\infty u(x, y, 0^\pm) \]
Pressure difference

• The difference between the pressures on either side of the wing is given by

\[ \Delta p = p(x, y, 0^-) - p(x, y, 0^+) = \rho U_\infty u(x, y, 0^+) - \rho U_\infty u(x, y, 0^-) \]

• Substituting from the \( u \) equation gives

\[ \Delta p = \rho U_\infty^2 \sin \alpha \frac{b(x)}{2\sqrt{b(x)^2 - 4y^2}} \frac{\partial b}{\partial x} + \rho U_\infty^2 \sin \alpha \frac{b(x)}{2\sqrt{b(x)^2 - 4y^2}} \frac{\partial b}{\partial x} \]

\[ = \rho U_\infty^2 \sin \alpha \frac{b(x)}{\sqrt{b(x)^2 - 4y^2}} \frac{\partial b}{\partial x} \]
Lift and drag

- The total aerodynamic force, \( N \), is the surface integral of \( \Delta p \) over the entire wing.

\[
N = \int_0^c \int_{-b(x)/2}^{b(x)/2} \rho U_\infty^2 \sin \alpha \frac{b(x)}{\sqrt{b(x)^2 - 4y^2}} \frac{\partial b}{\partial x} \, dy \, dx
\]

- The lift is the component of the total aerodynamic force perpendicular to the free stream.

- The drag is the component of the total aerodynamic force parallel to the free stream.
Lift and drag (2)

• For a triangular Delta wing

\[ b(x) = 2x \tan \Lambda = \frac{xAR}{2} \]

• Where \( \Lambda \) is the sweep angle.

• The lift and drag coefficients become

\[ C_L = 2\pi \tan \Lambda \sin \alpha \cos \alpha = \frac{\pi AR}{2} \sin \alpha \cos \alpha \]

\[ C_D = 2\pi \tan \Lambda \sin^2 \alpha = \frac{\pi AR}{2} \sin^2 \alpha = C_L \sin \alpha \]
Vortex lift

- Slender body theory is only valid at very low angles of attack
- Unfortunately, due to the low aspect ratio, Delta wings do not produce a lot of lift at low angles of attack
- Higher angles of attack must be used, but these are not modeled properly by slender body theory.
- A vortex lift term can be added to the potential lift to account for high angles of attack.
Delta wing tip vortices

• At higher angles of attack, strong vortices are generated at the leading edge.
• They generate high-speed flow and increase the lift significantly.
Vortex correction

- According to Houghton and Carpenter, the vortices generate an additional drag per unit length on each segment that is equal to

\[ \Delta N_V = \frac{1}{2} \rho (U_\infty \sin \alpha)^2 b(x) C_{DP} \]

- where \( C_{DP} \) is the drag of a flat plate perpendicular to a free stream and is equal to around 1.95.

- The total normal force due to the vortices is obtained by integrating over \( x \) from 0 to \( c \).

\[ N_V = \int_0^c \Delta N_V = \frac{1}{2} \rho U_\infty^2 C_{DP} \sin^2 \alpha \int_0^c b(x) dx = \frac{1}{2} \rho U_\infty^2 C_{DP} \sin^2 \alpha S \]
Vortex lift and drag

• The vortex lift and drag are then equal to
  \[ C_{Lv} = C_{DP} \sin^2 \alpha \cos \alpha \]
  \[ C_{Dv} = C_{DP} \sin^3 \alpha \]

• So that the total lift and drag are given by
  \[ C_L = \frac{\pi AR}{2} \sin \alpha \cos \alpha + C_{DP} \sin^2 \alpha \cos \alpha \]
  \[ C_D = \frac{\pi AR}{2} \sin^2 \alpha + C_{DP} \sin^3 \alpha \]
Polhamus’ method

- Polhamus considered the potential solution as well as the effect of leading edge suction.

Leading edge suction is a force perpendicular to the leading leading edge, parallel to the wing’s surface.
• Polhamus’ concept is that the lift due to the leading edge vortex is equal to the leading edge suction force but normal to the wing’s surface.

• Working through the maths he arrived at the following total lift

\[ C_L = K_P \sin \alpha \cos \alpha + K_V \sin^2 \alpha \cos \alpha \]
The coefficients $K_P$ and $K_V$ can be estimated from this diagram, as functions of Aspect Ratio.
Some more on drag

• The drag calculated from potential theory is \( C_D = C_L \sin \alpha \)

• Katz and Plotkin show that the leading edge suction force reduces the drag by 2, i.e. \( C_D = (C_L / 2) \sin \alpha \)

• If the Polhamus lift is substituted in this expression:

\[
C_D = \frac{K_p}{2} \sin^2 \alpha \cos \alpha + \frac{K_v}{2} \sin^3 \alpha \cos \alpha
\]
Vortex breakdown

- It is clear that, at higher angles of attack, the vortex lift can make a significant contribution to the total lift.
- Unfortunately, as the angle of attack increases further, the vortices break down and their beneficial effect disappears.
- Vortices always break down eventually, but the breakdown occurs off the wing’s surface at intermediate angles of attack.
- As the angle of attack increases, the breakdown point moves upstream and eventually onto the wing’s surface.
- An increase in Reynolds number can also move the breakdown point upstream.
Vortex breakdown

(a) $Re = 5000$

(b) $Re = 10000$

Experimental Aerodynamics
Practical Session

• Determine the aerodynamic characteristics of a Delta wing in the ULg wind tunnel.
• Carry out force measurements and surface flow visualization.
• Compare the measured drag and lift with the theoretical predictions. Is there good agreement? If not why?
• Use china clay visualization and wool tufts to visualize the surface flow and to observe the occurrence of vortex bursting.
• Write a short report (5 pages max).
Previous experiments
Katz and Plotkin

Experimental Aerodynamics

\[ C_L \]

Angle of attack (deg)

Equations:
- Eq. 8.94
- VSAERO, Ref. 9.2
- Panel method with L.E. separation (Ref. 12.13)

\[ \frac{\pi \alpha}{2} \]

\[ \alpha R = 1, \text{ Delta wing} \]
Flow visualization

• The most basic observation of the flow simulated in a wind tunnel is visualization.
• Unfortunately air is colorless and transparent – it cannot be seen.
• Several different methods for visualizing the flow exist:
  – Wool (cotton) tufts
  – China clay
  – Oil film
  – Smoke
  – PIV
Tufts

- Tufts are short lengths of yarn attached to the surface of a wind tunnel model.
- One end is fixed and the other is free. The tuft will align itself with the local surface flow. It will affect the aerodynamic forces.
- Tufts are glued or taped to the surface.
- Sometimes fluorescent tufts are used.
- Light makes the tufts more visible. Ultraviolet light on white tufts is very effective (e.g. white tee-shirts in night clubs)
- Tufts can also be placed on a grid in the wake of the model to visualize the wake
Tuft placement

- Tufts are usually taped or glued on the surface.
- Their placement depends on model geometry and flow dimensionality.
- Some arrangements are suitable for 2D flows, others for 3D flows.
Examples of tuft use

Fluorescent tufts, ultraviolet light source – demonstrates flow separation

Crochet yarn, white light source – demonstrates flow unsteadiness
More tufts

Wake and tuft wake visualization

In-flight tuft visualization
A mixture of kerosene, china clay (kaolin) and fluorescent paint is applied to the entire surface of the model with the wind off. Turning the wind on causes the kerosene to evaporate as it follows the streamlines. The china clay stays on the model, indicating the direction of the streamlines. A UV light can light up the painted china clay for nice photographs. The china clay can be easily wiped off after taking the photographs. Typical mix: 100ml of china clay per liter of kerosene. A simpler mixture is white spirit with crushed chalk.
The ULg wind tunnel has a very simple 1-component balance mounted under the turntable. It measures lift only using a load cell. Drag and side force can be measured using a strain gauged support on which the model can be attached.