Subsonic Wings

an introduction

and review

W.H. Mason

Configuration Aerodynamics Class
Topics

• Subsonic Wing Calculation Method Review
• Aero of High Aspect Ratio Wings
• Slender Wings
First, review a great tool to understand wing aero

**VLM Methods – a way to get insight**

- Linear, inviscid aerodynamics – strictly subsonic
- Ignores thickness – \( bc \)’s applied on the mean plane
  - VLM is essentially a 3D thin airfoil theory
- Finds \( \Delta C_p \), not the upper/lower surface pressures
- Very handy and accurate as seen below
- Really good for understanding interacting surface ideas

Choices: VLMpc, Tornado, AVL, JKayVLM, XFLR5, VSPaero
The classic method

- Each panel is modeled using a horseshoe vortex of as yet unknown strength (has bound and trailing vortex “legs”)
- The Biot-Savart Law is used to compute the induced velocity at a control point due to the contributions from each horseshoe vortex
- Summing up the contributions from each horseshoe vortex and satisfying the boundary conditions leads to a linear system of algebraic equations for the unknown vortex strengths

Need to include the contributions from both sides of the wing!

Usually employs a flat wake to downstream infinity – a linear problem
To complete the method

• The classical VLM method puts the bound vortex on the \( \frac{1}{4} \) chord of the panel, and the control point is placed at the \( \frac{3}{4} \) chord point
• The boundary condition satisfies the angle of attack, the camber slope, and the wing twist. They are simply added up so that you can pick how to divide up the contributions. This is basically a bookkeeping problem.
• Solving the linear system for the horseshoe vortex strengths is an *analysis* problem.
• Using the same system, but specifying the vortex strengths you can find the required camber and twist, a *design* problem
• Many variations have been used, lots of Refs in the text.
VLM Models and Tips

Model Tips
- start simple
- crude representation of the planform is all right
- keep centroids of areas the same: actual planform to \textit{vlm} model

line up spanwise breaks on a common break, and make the edge streamwise

Make edges streamwise

first planform

second planform
Convergence with number of “panels”

F/A-18

Vortex Lattice Method

\( \Delta \text{Neutral point, percent } \bar{c} \)

(5)

(9)

Total number of panels

\( \text{Number of chordwise panels} \)
Panel Models

Vortex Lattice
233 panels

Woodward
208 panels

Pan Air
162 panels
F-15 3-Surface VLM Model
## Three-Surface F-15 Longitudinal Derivatives

### Table 1
Three-Surface F-15 Longitudinal Derivatives

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Neutral Point (% mac)</th>
<th>$C_{ma}$ (per deg.)</th>
<th>$C_{L\alpha}$ (per deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M = 0.2</td>
<td>Wind Tunnel</td>
<td>15.70</td>
<td>0.00623</td>
</tr>
<tr>
<td></td>
<td>Vortex Lattice</td>
<td>15.42</td>
<td>0.00638</td>
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<tr>
<td></td>
<td>Woodward</td>
<td>14.18</td>
<td>0.00722</td>
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<tr>
<td></td>
<td>Pan Air</td>
<td>15.50</td>
<td>0.00627</td>
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<tr>
<td>M = 0.8</td>
<td>Wind Tunnel</td>
<td>17.70</td>
<td>0.00584</td>
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<td></td>
<td>Vortex Lattice</td>
<td>16.76</td>
<td>0.00618</td>
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<tr>
<td></td>
<td>Pan Air</td>
<td>15.30</td>
<td>0.00684</td>
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<tr>
<td>M = 1.6</td>
<td>Wind Tunnel</td>
<td>40.80</td>
<td>-0.01040</td>
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<tr>
<td></td>
<td>Woodward</td>
<td>48.39</td>
<td>-0.01636</td>
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</tbody>
</table>
Canard Height Effect

![Graph showing the effect of canard height on neutral point and lift coefficient per degree.](image)
F-15 horizontal tail effectiveness

\[ C_m \delta_H \text{ per deg.} \]

\[ C_l \delta_H \text{ per deg.} \]

Mach Number

Wind tunnel
Vortex lattice
Woodward
F-15 aileron effectiveness

![Graph showing F-15 aileron effectiveness]

- Wind tunnel ($\delta_a = \pm 20^\circ$)
- Vortex lattice: Sym chordwise panels
  - 6
  - 8
  - 10

$C_{l\delta_a}$ per deg.

Mach Number
Warren-12 Test Case

\[
AR = 2\sqrt{2} \\
\Lambda_{LE} = 53.54^\circ \\
S_{wing} = 2\sqrt{2} \\
C_{L\alpha} = 2.743 / \text{rad} \\
C_{M\alpha} = -3.10 / \text{rad}
\]

Note: \(C_M\) about wing apex, Reference chord is 1.0
Comment: Reference Area(s)

The key:
Define it for others!

Most calculations refer to gross area which includes projected areas within fuselages and nacelles.

The reference trap wing

Source: Stinton, Design of the Airplane
For More On Calculation Methods

http://www.cambridge.org/us/academic/subjects/engineering/aerospace-engineering/applied-computational-aerodynamics-modern-engineering-approach
Aerodynamics of High Aspect Ratio Ratio Wings

- Planforms
- Spanloads
- Pitching moment and pitchup
- Aerodynamic Center
- Isobars/Twist
- Camber
- 2D-3D connection
- Canard and Ground Effects
## Typical Planform Characteristics of Transport Aircraft

<table>
<thead>
<tr>
<th>1st Flight</th>
<th>Aircraft</th>
<th>W/S</th>
<th>AR</th>
<th>$\Lambda_{c14}$</th>
<th>$\lambda$</th>
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<tbody>
<tr>
<td>1957</td>
<td>B707-120</td>
<td>105.6</td>
<td>7.04</td>
<td>35.0</td>
<td>0.293</td>
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<td>1958</td>
<td>DC-8-10</td>
<td>111.9</td>
<td>7.32</td>
<td>30.0</td>
<td>0.230</td>
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<tr>
<td>1963</td>
<td>B707-320C</td>
<td>110.0</td>
<td>7.06</td>
<td>35.0</td>
<td>0.250</td>
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<tr>
<td>1970</td>
<td>B747-200B</td>
<td>149.1</td>
<td>6.96</td>
<td>37.5</td>
<td>0.254</td>
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<td>1970</td>
<td>L-1011</td>
<td>124.4</td>
<td>8.16</td>
<td>35.0</td>
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<td>1972</td>
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<td>35.0</td>
<td>0.230</td>
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<td>1972</td>
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<td>7.78</td>
<td>28.0</td>
<td>0.230</td>
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<tr>
<td>1982</td>
<td>A310-100</td>
<td>132.8</td>
<td>8.80</td>
<td>28.0</td>
<td>0.260</td>
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<tr>
<td>1986</td>
<td>B767-300</td>
<td>115.1</td>
<td>7.99</td>
<td>31.5</td>
<td>0.182</td>
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<tr>
<td>1988</td>
<td>B747-400</td>
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<td>7.61</td>
<td>37.5</td>
<td>0.240</td>
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<tr>
<td>1990</td>
<td>MD-11</td>
<td>166.9</td>
<td>7.57</td>
<td>35.0</td>
<td>0.230</td>
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<tr>
<td>1992</td>
<td>A330</td>
<td>119.0</td>
<td>9.30</td>
<td>29.7</td>
<td>0.192</td>
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<tr>
<td>1994</td>
<td>B777-200</td>
<td>118.3</td>
<td>8.68</td>
<td>31.6</td>
<td>0.172</td>
</tr>
</tbody>
</table>

data courtesy Nathan Kirschbaum
Clearly the A380 pays a price to satisfy the 80 meter gate box limit
Forward, Unswept and Aft Swept Planforms, AR = 2.8
Related Spanloads and Section Lift Coefficients

For an untwisted planar wing

Warren 12 planform, sweep changed

Spanload, \( cc_1 / c_a \)

Section \( C_L \)

y/(b/2)
Forward, Unswept and Aft Swept Planforms, $AR = 8$
For an untwisted planar wing
Example: VLM Pitching Moment agrees well with data until wing pitchup

data from NACA RM A50K27

$AR = 10, \Lambda_{c/4} = 35^\circ, \lambda = 0.5$

$Re = 10 \text{ million}$

$x_{ref} = \bar{c}/4$

VLMpc calculation
A confusion factor with modern wings
The LE and TE are scheduled with Mach and Alpha

From AIAA F-16 Case Study

**Automatic Variable Camber**

- **Take-off & Landing**
  - $\delta = 20^\circ$
  - Variable camber shapes airfoil to match flight condition
    - Maximizes Lift/Drag Ratio
    - Improves Directional Stability
    - Minimizes Buffet

- **Subsonic Cruise**
  - Basic airfoil

- **High-'g'-Maneuver**
  - $\delta = 25^\circ$

- **Supersonic Flight**
  - $\delta = \cdot 20^\circ$
  - $\delta = \cdot 2^\circ$

*Leading edge flap automatically programmed for best flap position (max lift/drag as a function of Mach number and angle-of-attack)*
Note – the curves don’t go to 0.25 at 0 deg sweep!

Aerodynamic Center Variation with Sweep

Vortex Lattice Analysis
NS = 25, NC = 8 (200 panels)

AR = 10, taper = 0.5

AR = 6, taper = 1/3
Low Aspect Ratio Wing Neutral Point \((ac)\)

For a rectangular wing it moves forward!

From Schlichting and Truckenbrodt, *Aerodynamics of the Airplane*

Discovered while making pre-test estimates

Inboard Wing built/tested at VT
Isobars on untwisted/uncambered swept wing - needs aero design!

Note: this is actually a transonic case, \( M = 0.93, \alpha = 2^\circ \) from AFFDL-TR-77-122, February 1978.

These funny NACA report numbers denote series classified at the time, “L” stands for Langley, reports starting with “A” denote Ames

Without twist and camber: don’t get full effect of sweep
Now: Design
Typical Twist Distributions
- to improve isobars/spanloads -

from LAMDES on the software website

Aft Swept Wing

Forward Swept Wing

A LAMDES artifact
Design
Typical Camber Variation

Cambers from the LAMDES code on the software website
The airfoil problem is converted to 2D (normal), solved (designed), and put in the wing 3D

\[ c_{2D} = c_s \cos \Lambda \]
\[ M_{2D} = M_\infty \cos \Lambda \]
\[ \frac{t}{c}_{2D} = \frac{t}{c}_s \frac{1}{\cos \Lambda} \]
\[ c_{L2D} = \frac{c_{Ln}}{\cos^2 \Lambda} \]
Now Canards
Canard-Wing Interaction

- Canard wake extends to infinity
- Wing wake not shown

Downwash from canard across wing at Section A-A

Upwash outboard of canard tips
Look at example from WT testing

Wing tested at NASA Langley, NASA TN D-7910 by Blair Gloss

Several combinations tested, we illustrate the outlined wing and canard

Note: all the test results are tabulated in the NASA TN
Canard Effects on Lift and Moment

Canard Effect on Lift
- minimal at low alpha -

Canard Effect on Pitching Moment
- large effect on moment -

NASA TN D-7910 by Blair Gloss
Example for Minimum Induced Drag Calculations

Sample case in John Lamar’s NASA TN with LAMDES
Canard Wing Induced Drag

Note: The sample case may not be a good design, the canard is too big.

Canard height above wing $z/b$

Computations from LamDes

$M = 0.3, C_L = 0.5$

Canard lift must be negative to trim

Advantage of vertical separation clearly evident

Static Margin

Stable

Unstable

Advantage of relaxed static stability evident

$C_{Di}$
Actual twist values are heavily dependent on the canard load!
Some Variations: Tip treatment

A Whitcomb “winglet”

The “Raked Wingtip” used on the Boeing 767-400

Rounding the intersection leads to a “blended winglet”

Note “Yehudi”

from Feifel, in NASA SP-405, 1976

from Kroo, Ann. Rev. of Fluid Mech., 2001
Ground Effects from VLM

Solid lines: computed using JKayVLM
Dashed lines: from Kalman, Rodden and Giesing
Symbols: Experimental data

$C_{L\alpha}$ vs. $h/c$

$C_{M\alpha}$ vs. $h/c$
But ground effect can be complicated

A G650 crashed in New Mexico, April 2, 2011 – both pilots died

Why? $C_{L_{max}}$ IGE can be less than $C_{L_{max}}$ OGE with flaps down

Data showed adverse flap effects for $C_{L_{max}}$,
NACA TN 705, 1939

IGE: 
In Ground Effect

OGE: 
Out of Ground Effect
A completely new category
Slender Wings

See NASA CP 2416
Consider Two Entirely Different Wing Concepts

Think of high aspect ratio wings as having airfoils. Slender wings don’t have “airfoils” per say, Instead, think of spanwise sections.

High aspect ratio wings approach the $2\pi$ slope. The slender wing slope is $(\pi/2)AR$
Laser Light Sheet Leading Edge Vortex Flow

Light Sheet is a great way to see the LE vortex

Northrop IR & D example of flow over a delta wing configuration.

Exhibited at the 36th Paris air show.

Aviation Week & Space Technology, July 29, 1985
Drawback?
It’s “draggy” lift

Thanks to James Stewart you can see a video of the flowfield:
https://www.youtube.com/watch?v=5_jt4x_TpOI
The Polhamus LE Suction Analogy

Edward C. Polhamus,
NASA TN D-3767
Another View of the Suction Analogy

R.M. Kulfan, Wing Geometry Effects on Leading Edge Vortices, AIAA 79-1872
Results of the Polhamus Suction Analogy

$\alpha$

$\Lambda = 69.4^\circ$

$\text{AR} = 1.5$

Experimental data from Bartlett and Vidal

Prediction from Polhamus Leading Edge Suction Analogy

Vortex Lift

Potential Lift
Reduce Drag with a *Vortex Flap*?

*Flight International*, 16 March 1985

This concept was briefly popular, but it proved too hard to achieve.
Strakes are also low aspect ratio slender wings. Because they don’t stall, even low tail designs can have a nose-down moment problem.

This is a Hybrid Wing Concept

F-16

Forebody
Strakes

Note: you can apply the LE Suction Analogy to the strake in VLMpc

Note: Eventually the horizontal tail size was increased 25%
The Concorde Exploited Both Ground Effects and Vortex Lift to be Even Somewhat Practical

From Poisson-Quinton, Sustained Supersonic Cruise Aircraft Experience
And VLM works for Hypersonic Class Concepts

To Conclude

This just gives you the very basics
- no end to planform concepts, invent one yourself!