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

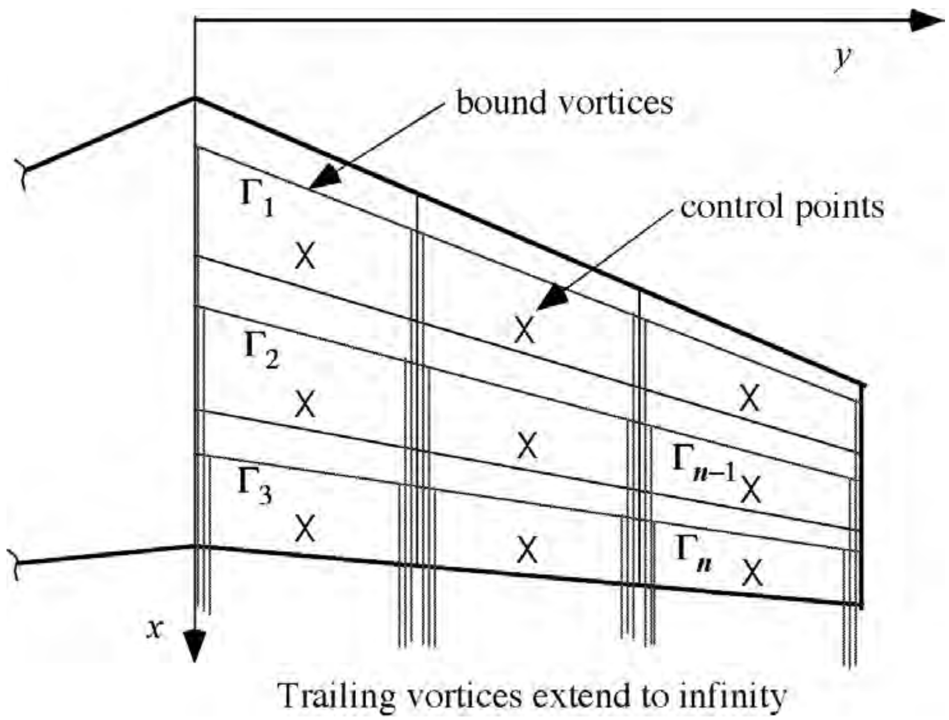
First, review a great tool to understand wing aero

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 ΔCp, 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



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

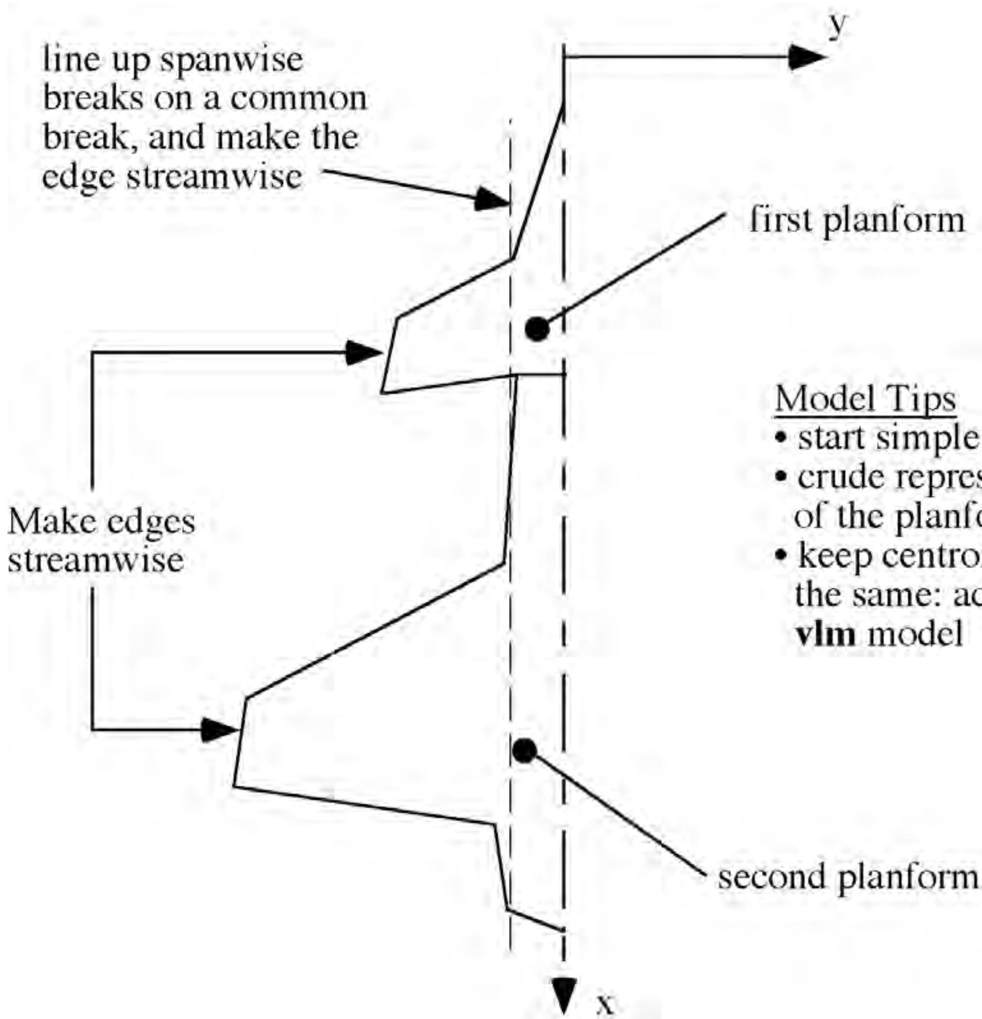
Usually employs a flat wake to downstream infinity – a linear problem

- 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

To complete the method

- The classical VLM method puts the bound vortex on the ¼ chord of the panel, and the control point is placed at the ¾ 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.

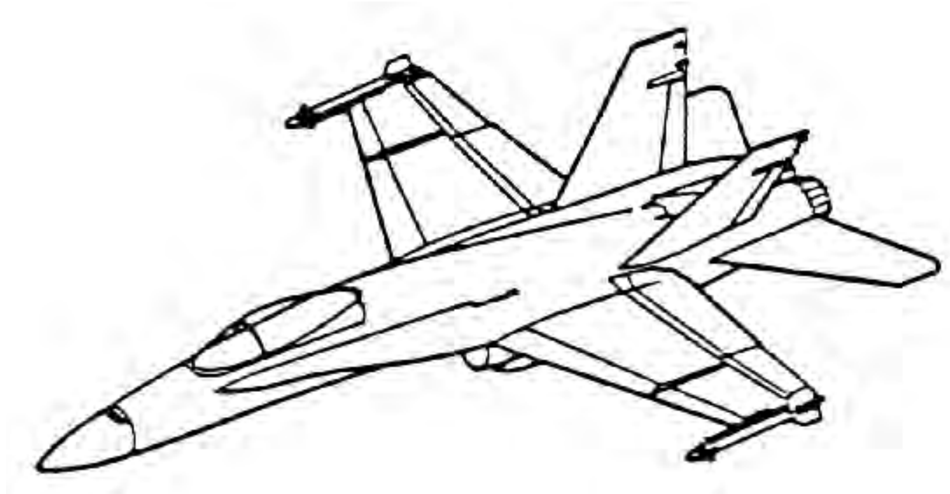
VLM Models and Tips

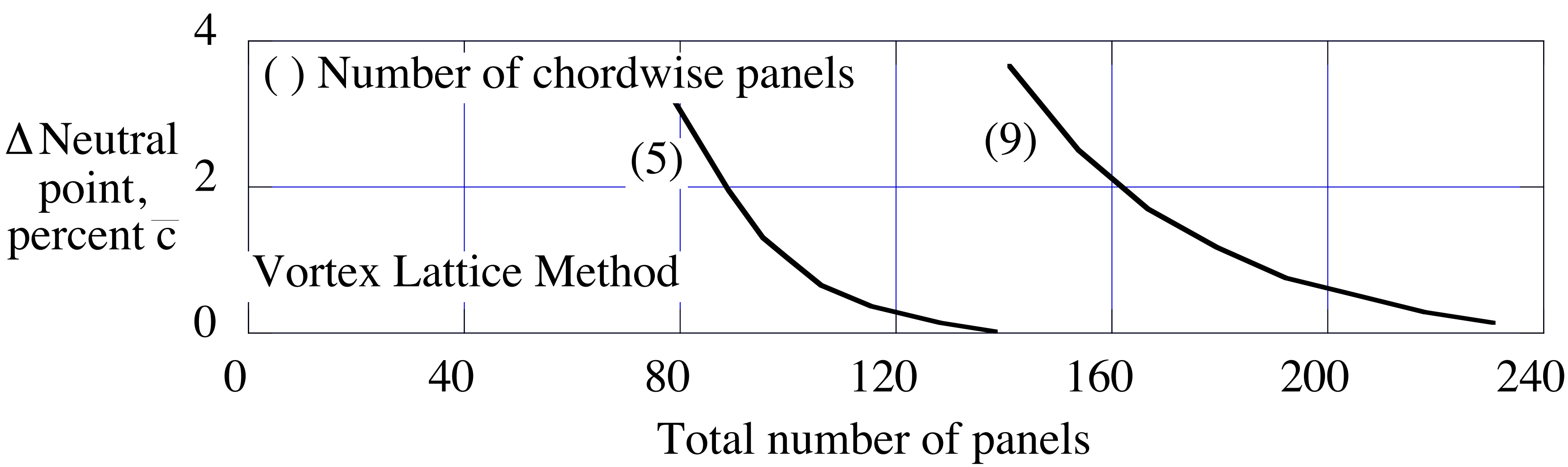


Model Tips
- start simple
- crude representation of the planform is all right
- keep centroids of areas the same: actual planform to **vlm** model

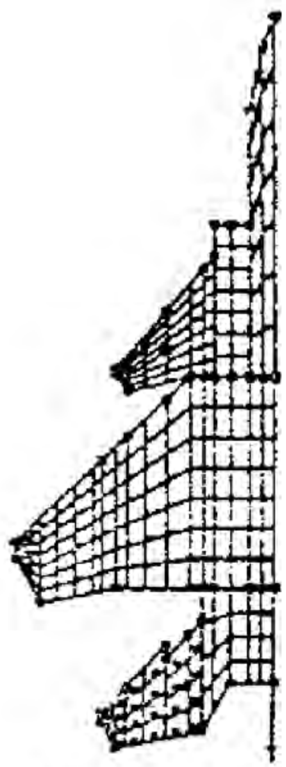
Convergence with number of “panels”

F/A-18

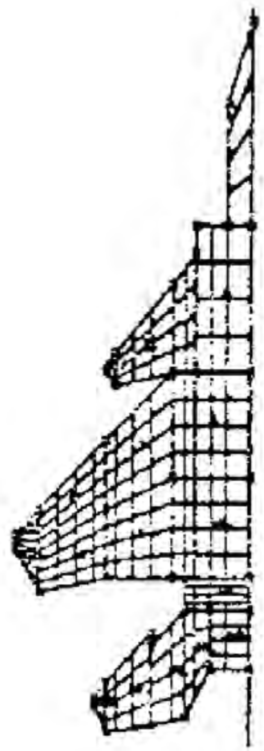




Panel Models



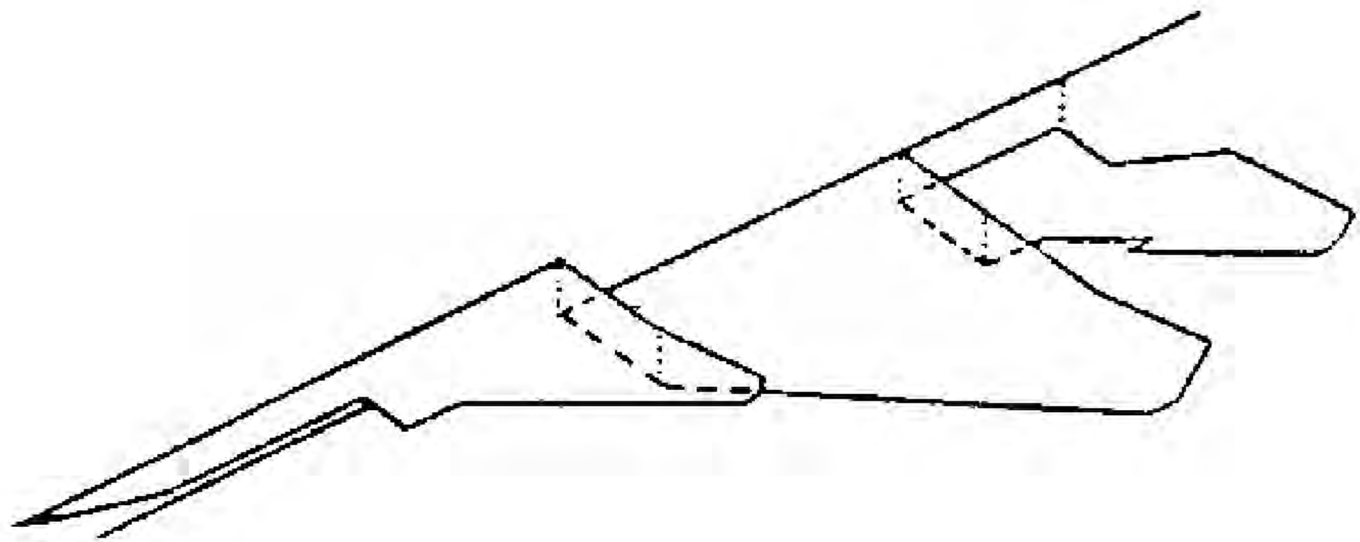
Vortex Lattice
233 panels



Woodward
208 panels

Pan Air
162 panels

F-15 3-Surface VLM Model

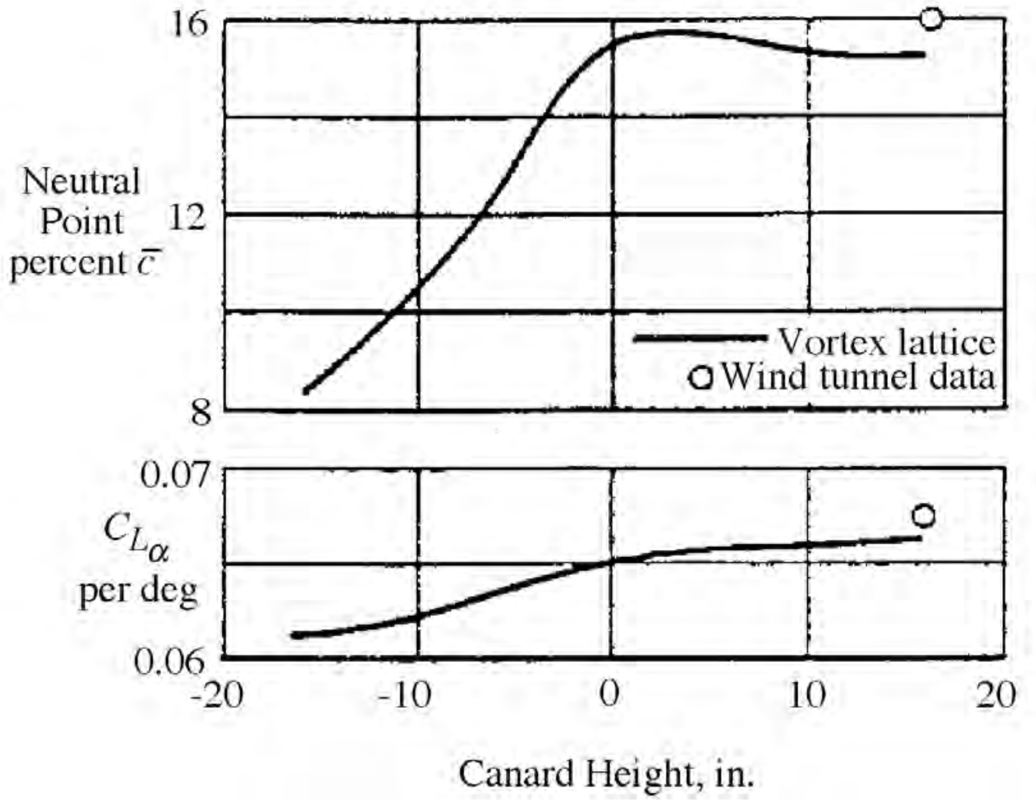


Three-Surface F-15 Longitudinal Derivatives

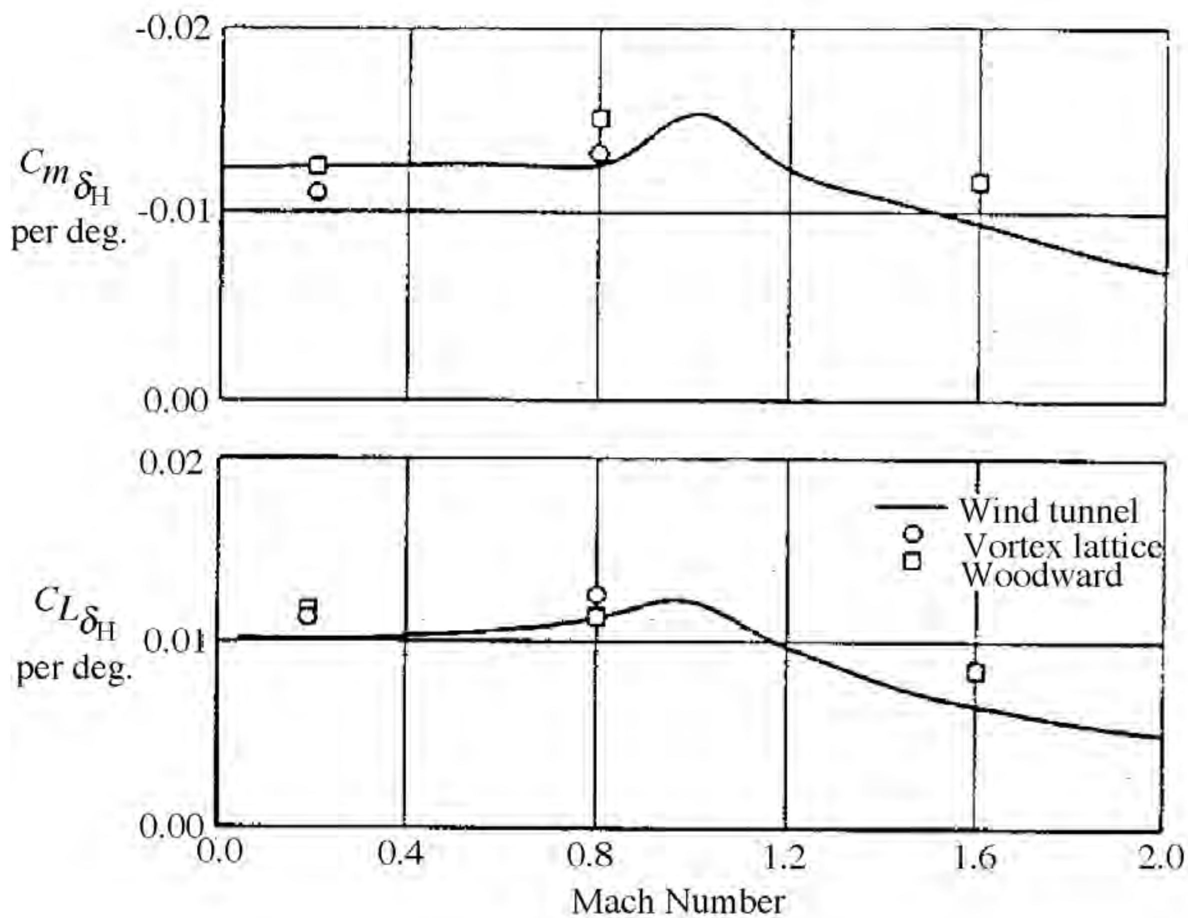
Table 1
Three-Surface F-15 Longitudinal Derivatives

Data Source		Neutral Point (% mac)	$C_{m\alpha}$ (per deg.)	$C_{L\alpha}$ (per deg.)
M = 0.2	Wind Tunnel	15.70	0.00623	0.0670
	Vortex Lattice	15.42	0.00638	0.0666
	Woodward	14.18	0.00722	0.0667
	Pan Air	15.50	0.00627	0.0660
M = 0.8	Wind Tunnel	17.70	0.00584	0.0800
	Vortex Lattice	16.76	0.00618	0.0750
	Pan Air	15.30	0.00684	0.0705
M = 1.6	Wind Tunnel	40.80	-0.01040	0.0660
	Woodward	48.39	-0.01636	0.0700

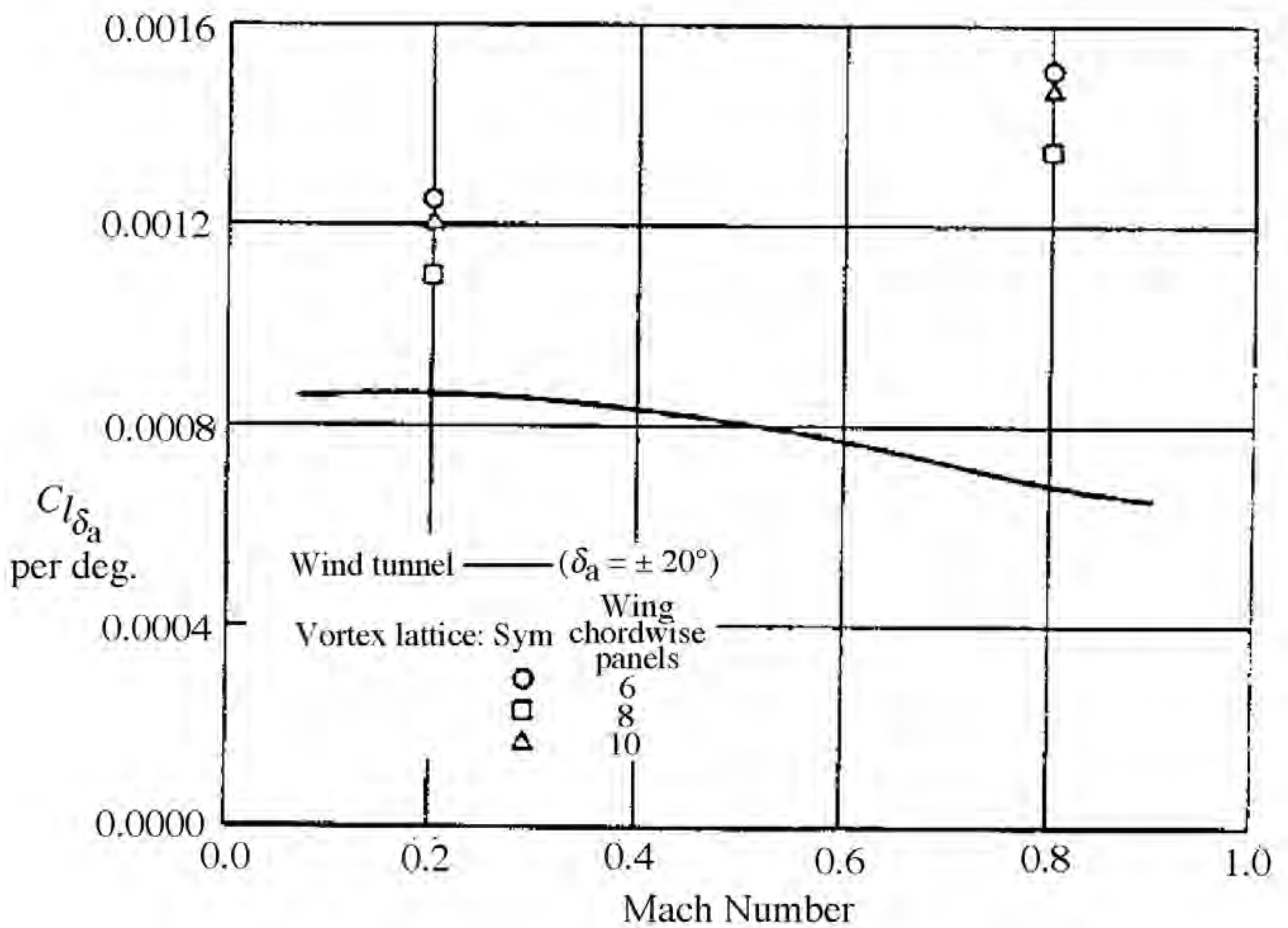
Canard Height Effect



F-15 horizontal tail effectiveness



F-15 aileron effectiveness



Warren-12 Test Case

$AR = 2\sqrt{2}$

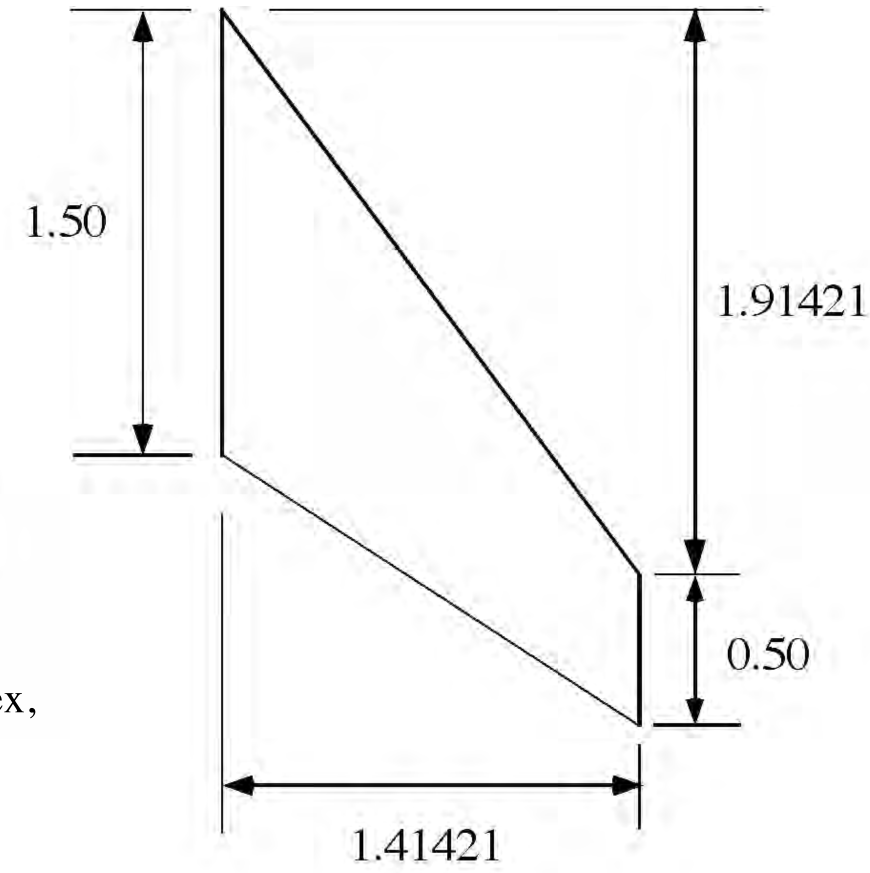
$\Lambda_{LE} = 53.54°$

$S_{wing} = 2\sqrt{2}$

$C_{L\alpha} = 2.743$ / rad

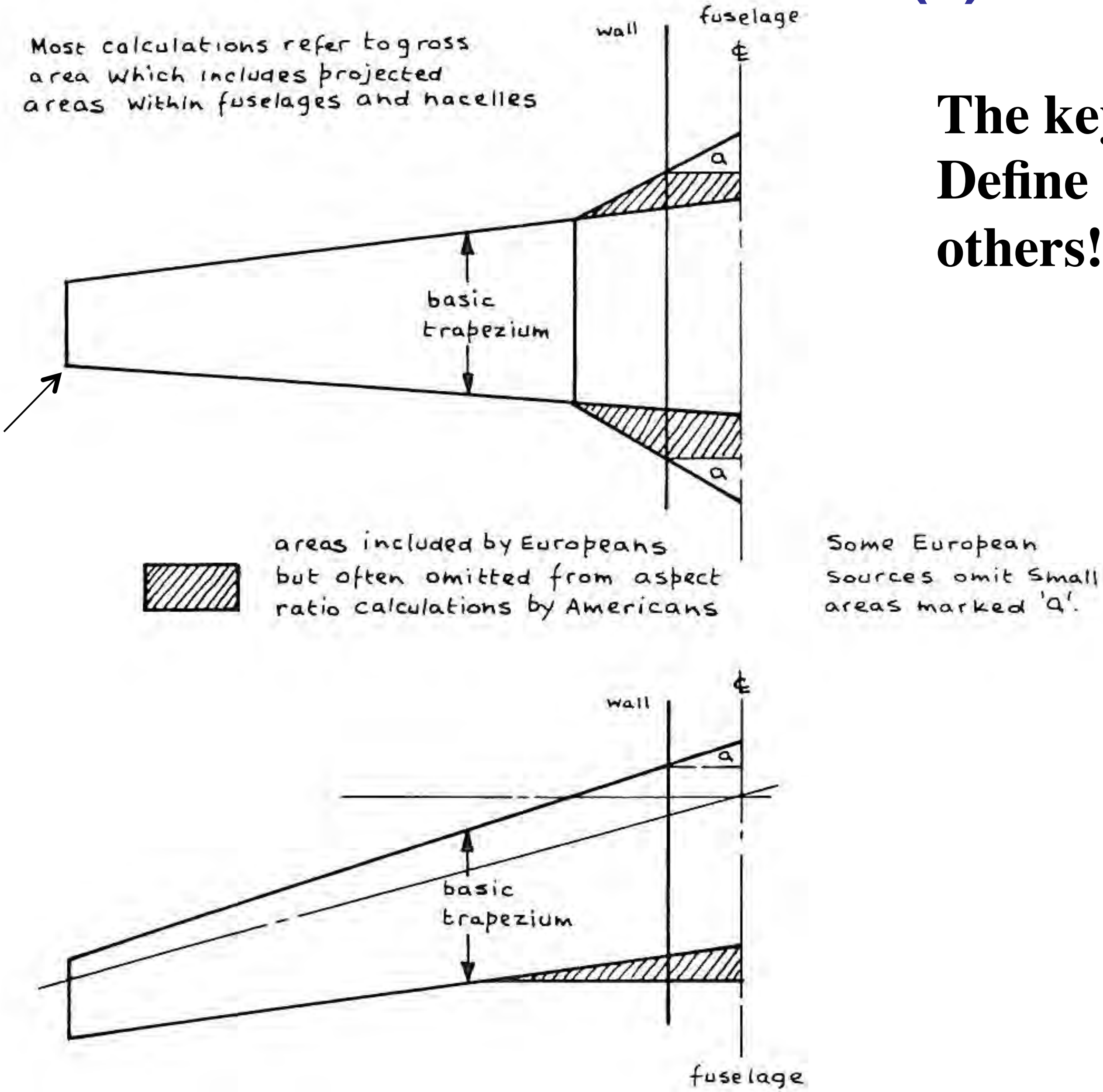
$C_{M\alpha} = -3.10$ / rad

Note: C_M about wing apex,
Reference chord is 1.0



Warren-12 Planform

Comment: Reference Area(s)

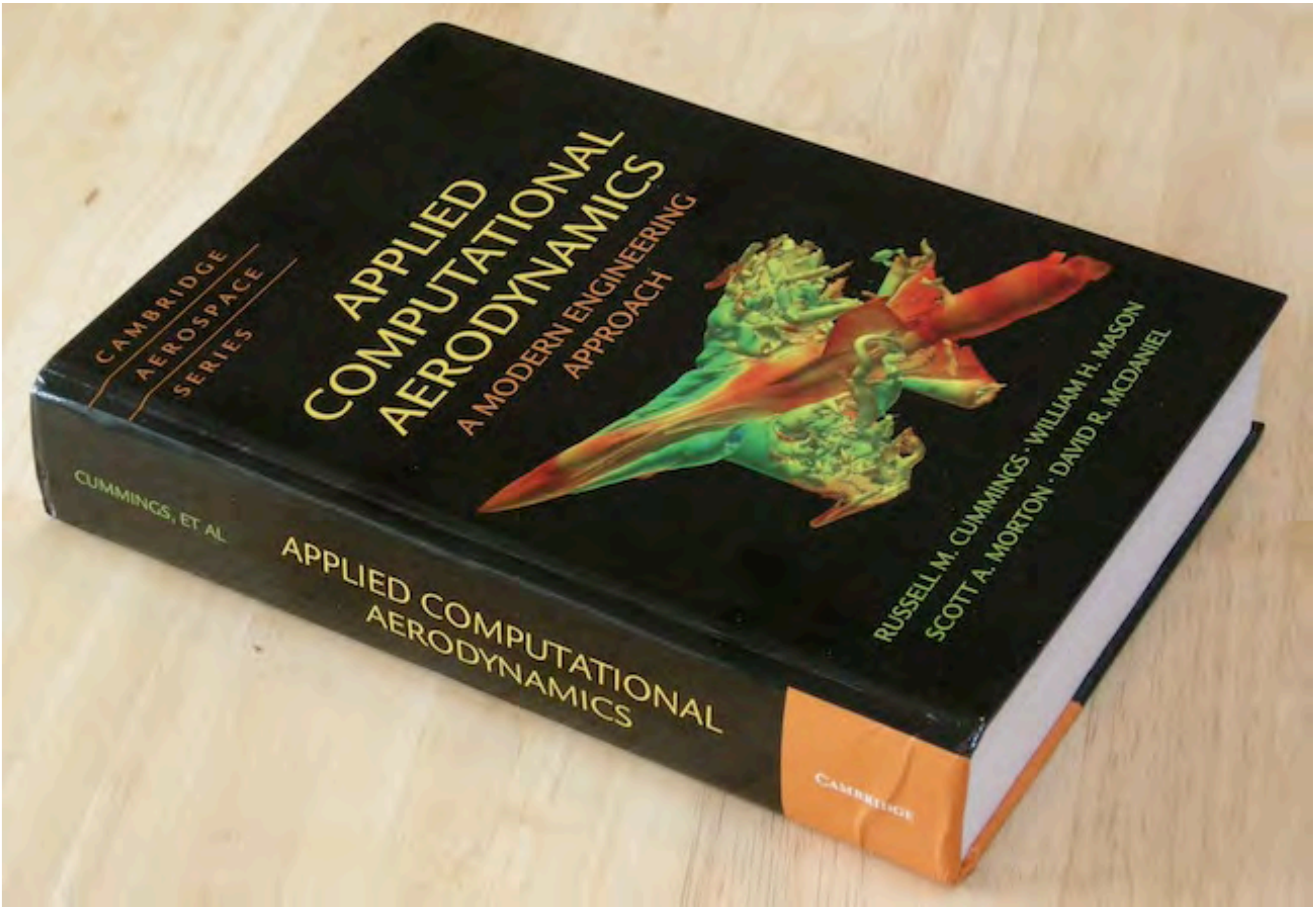


The reference trap wing

The key: Define it for others!

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 Wings

- Planforms
- Spanloads
- Pitching moment and pitchup
- Aerodynamic Center
- Isobars/Twist
- Camber
- 2D-3D connection
- Canard and Ground Effects

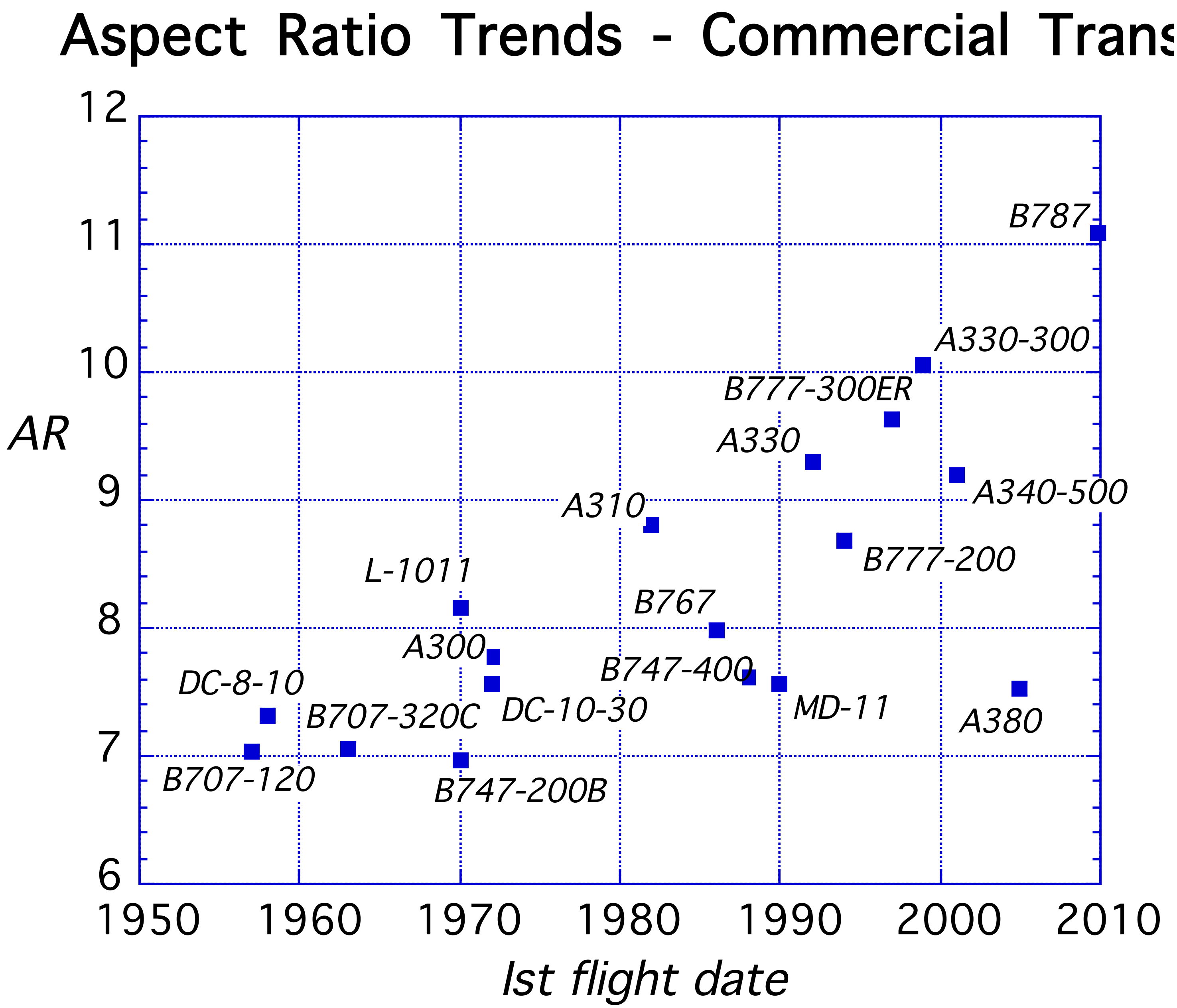
Typical Planform Characteristics of Transport Aircraft

Table 6-2

Typical Planform Characteristics of Major Transport Aircraft

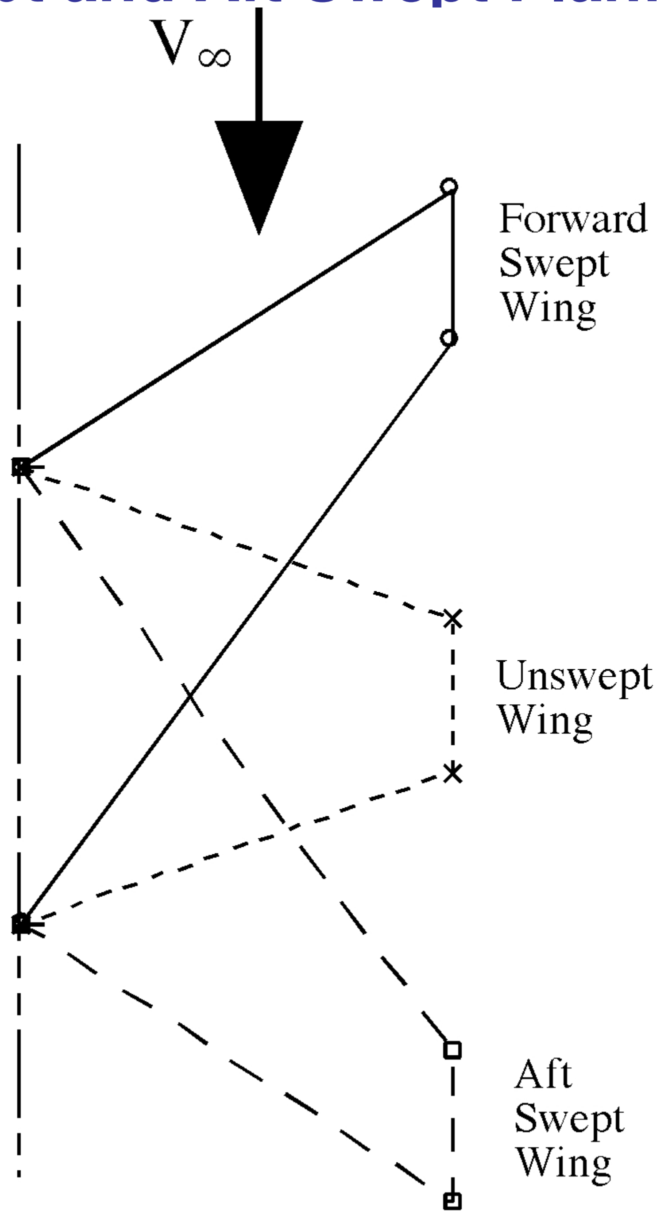
1^{st} Flight	Aircraft	W/S	AR	$\Lambda_{c/4}$ °	λ
1957	B707-120	105.6	7.04	35.0	0.293
1958	DC-8-10	111.9	7.32	30.0	0.230
1963	B707-320C	110.0	7.06	35.0	0.250
1970	B747-200B	149.1	6.96	37.5	0.254
1970	L-1011	124.4	8.16	35.0	0.200
1972	DC-10-30	153.7	7.57	35.0	0.230
1972	A300 B2	107.9	7.78	28.0	0.230
1982	A310-100	132.8	8.80	28.0	0.260
1986	B767-300	115.1	7.99	31.5	0.182
1988	B747-400	149.9	7.61	37.5	0.240
1990	MD-11	166.9	7.57	35.0	0.230
1992	A330	119.0	9.30	29.7	0.192
1994	B777-200	118.3	8.68	31.6	0.172

data courtesy Nathan Kirschbaum

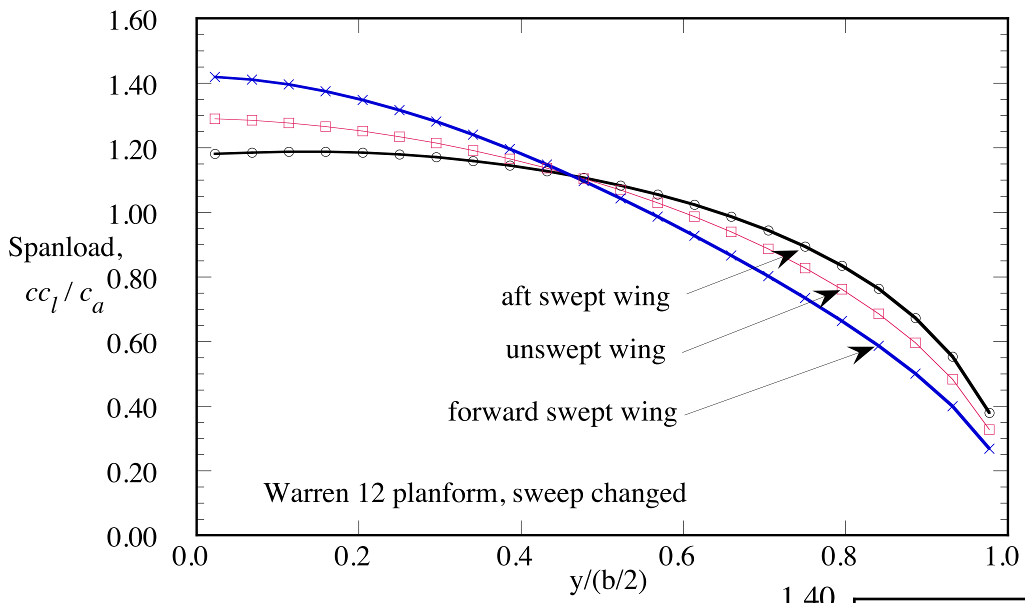


Clearly the A380 pays a price to satisfy the 80 meter gate box limit

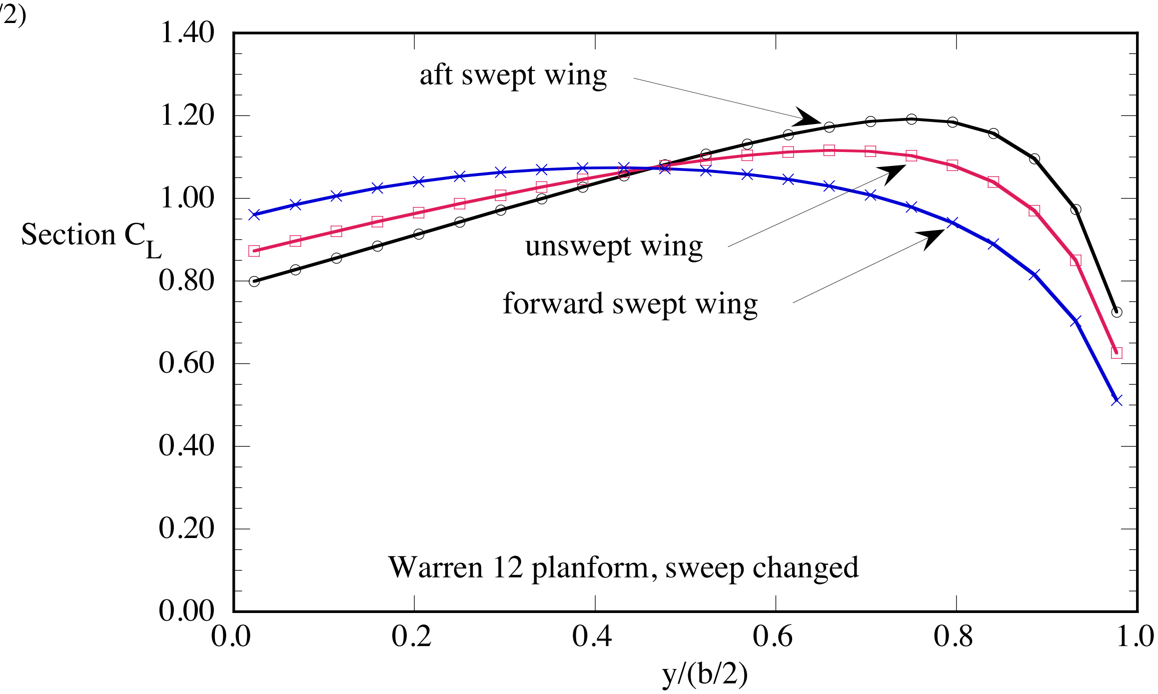
Forward, Unswept and Aft Swept Planforms, AR = 2.8



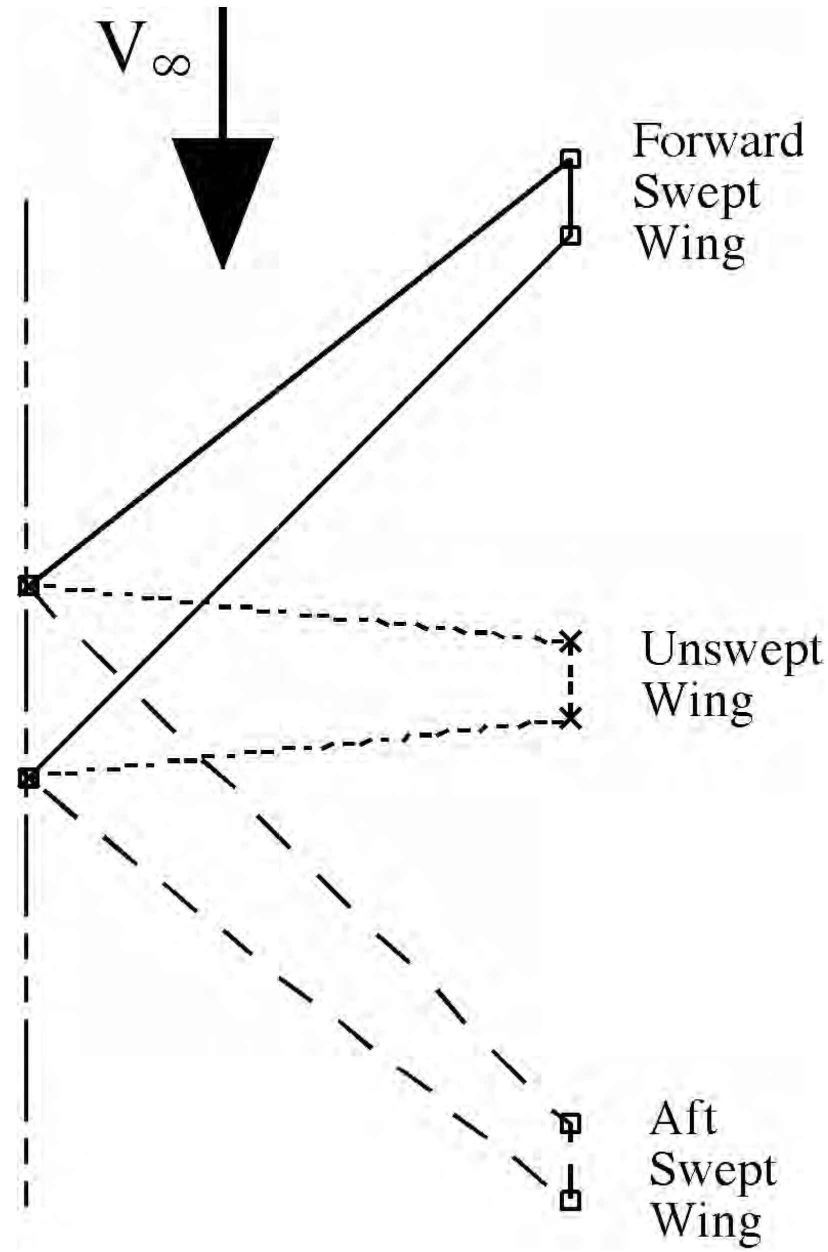
Related Spanloads and Section Lift Coefficients



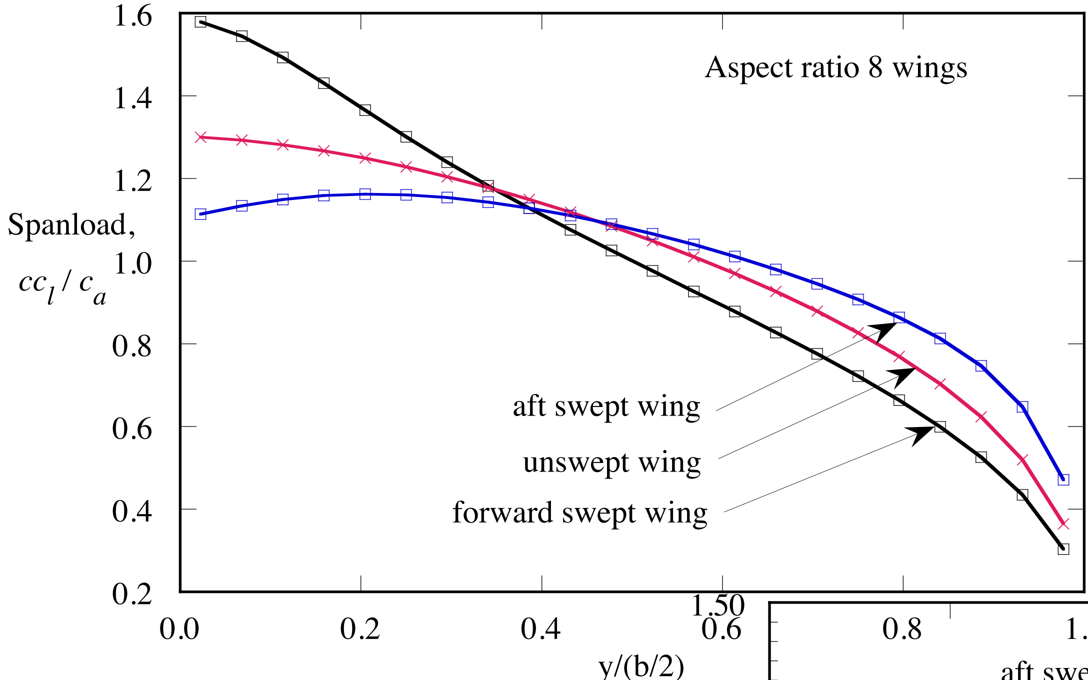
For an untwisted planar wing



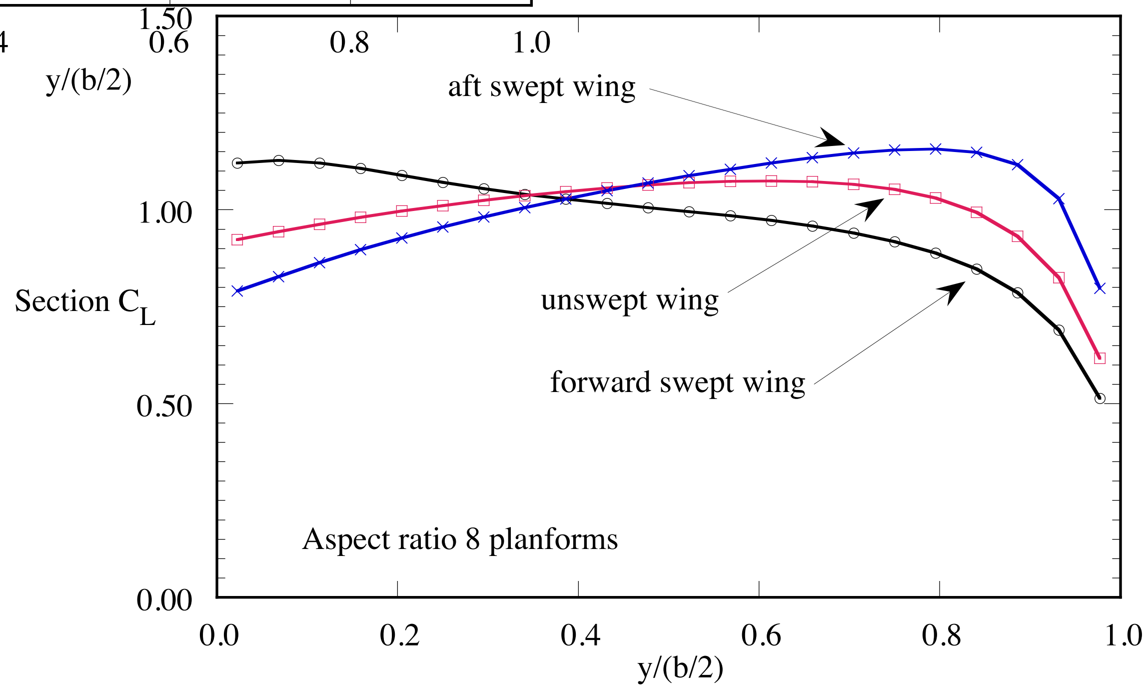
Forward, Unswept and Aft Swept Planforms, AR = 8



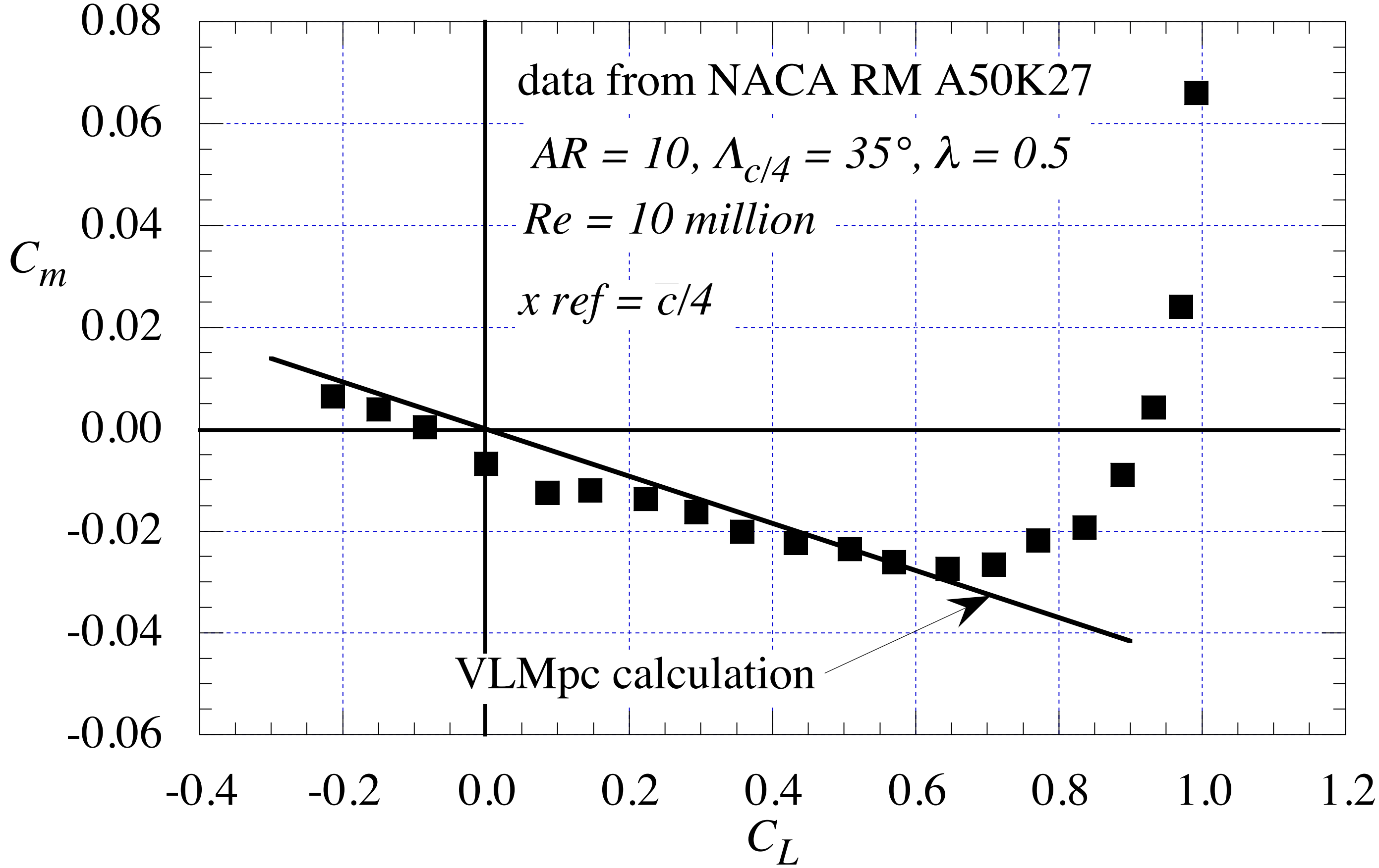
Related Spanloads and Section Lift Coefficients



For an untwisted planar wing

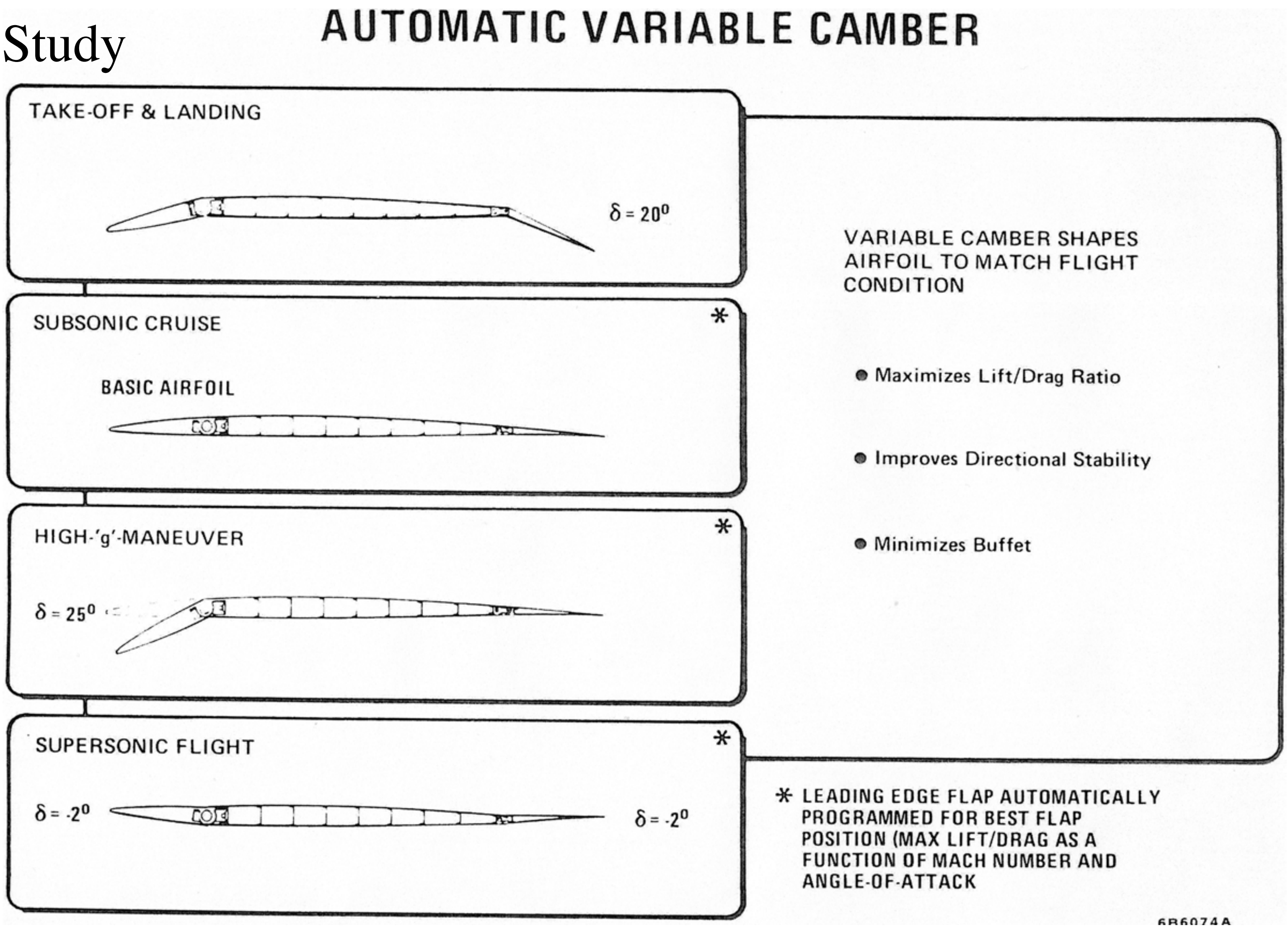


Example: VLM Pitching Moment agrees well with data until wing pitchup

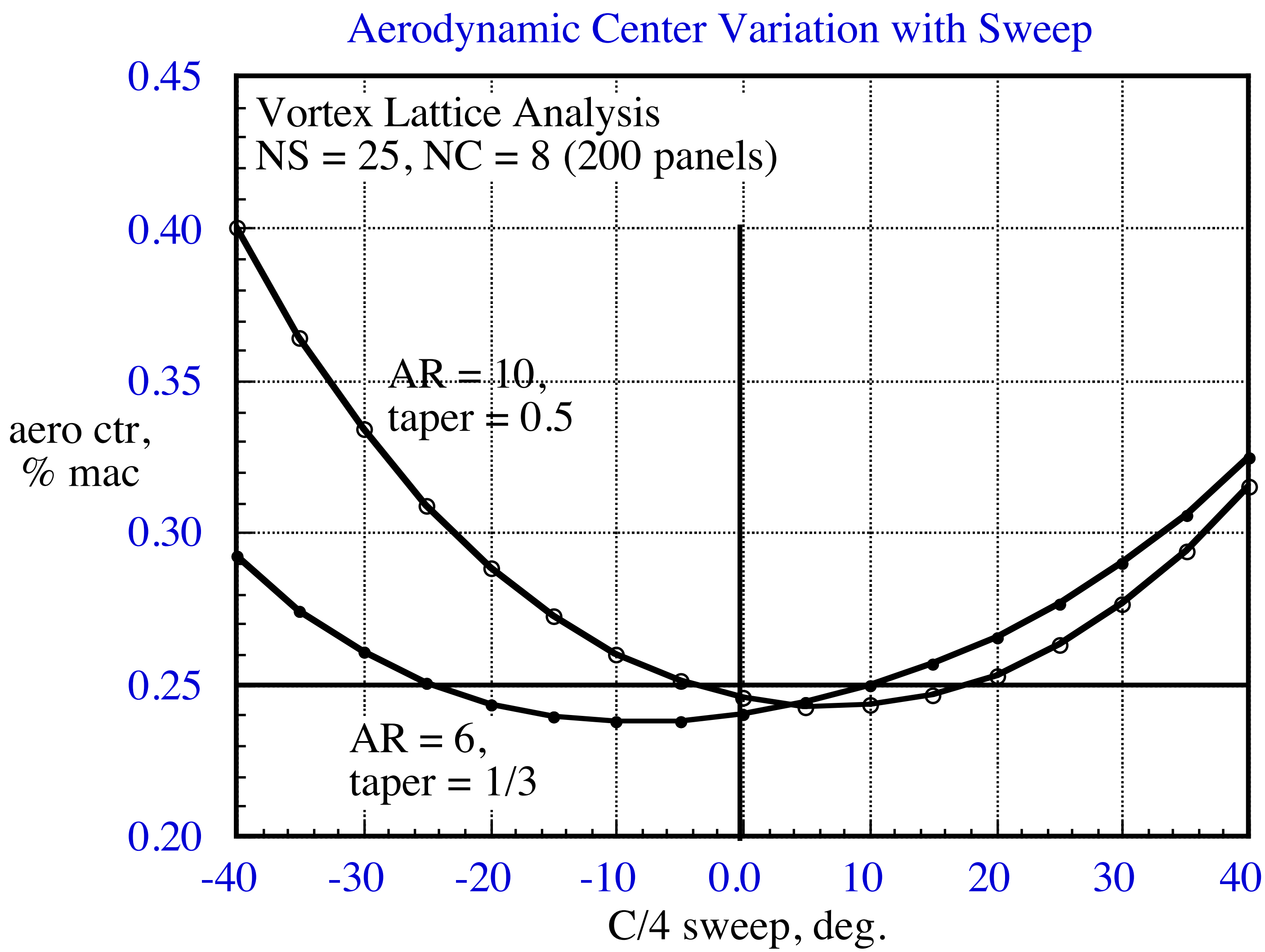


A confusion factor with modern wings
The LE and TE are scheduled with Mach and Alpha

From AIAA F-16
Case Study



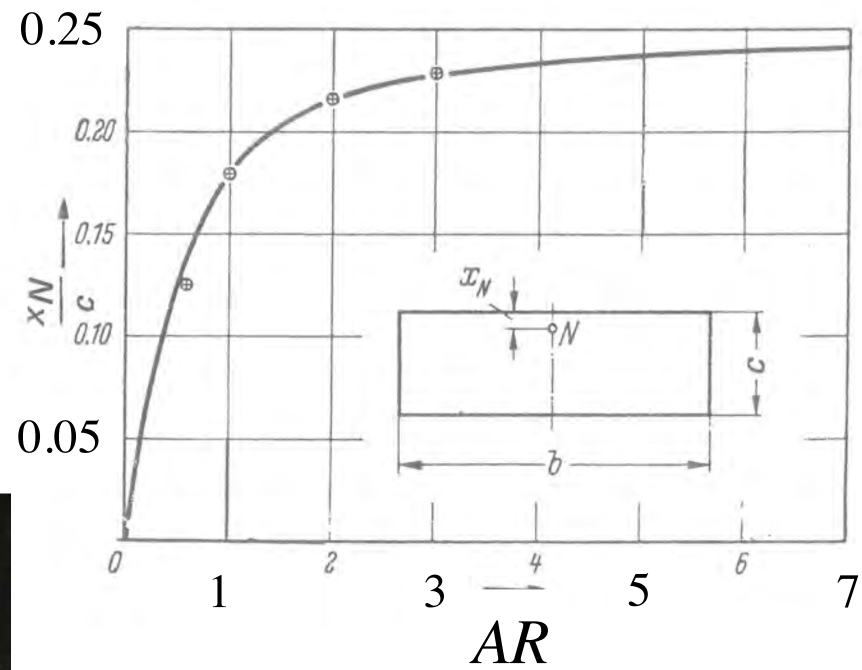
Note – the curves don't go to 0.25 at 0 deg sweep!



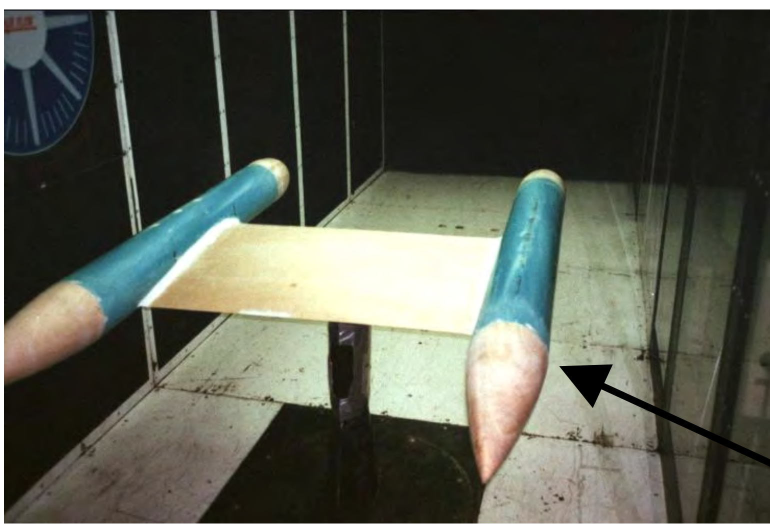
Low Aspect Ratio Wing Neutral Point (*ac*)

For a rectangular wing it moves forward!

From Schlichting and Truckenbrodt, *Aerodynamics of the Airplane*

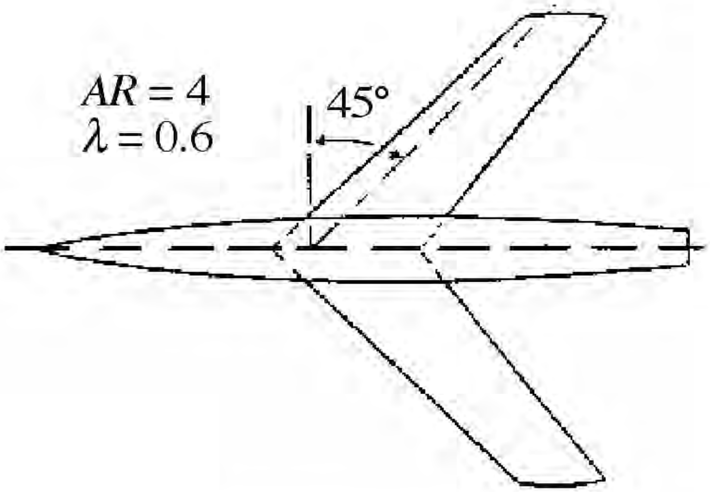


Discovered while making pre-test estimates



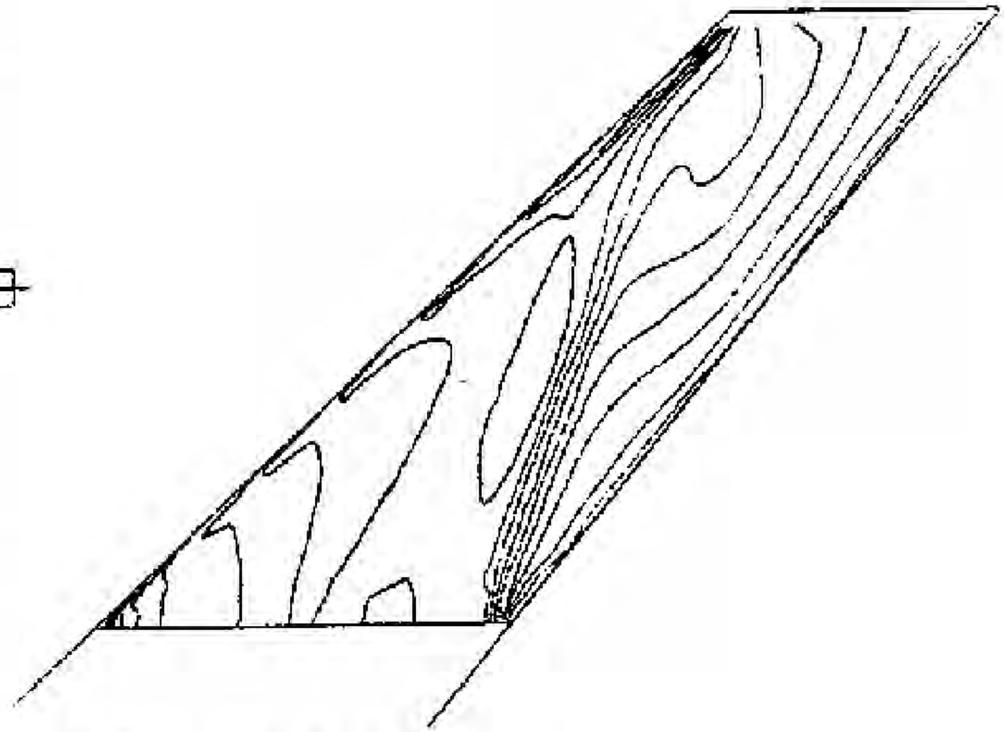
Inboard Wing built/tested at VT

Isobars on untwisted/uncambered swept wing - needs aero design!



(a) L51F07 configuration

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



(b) Upper Surface Isobars

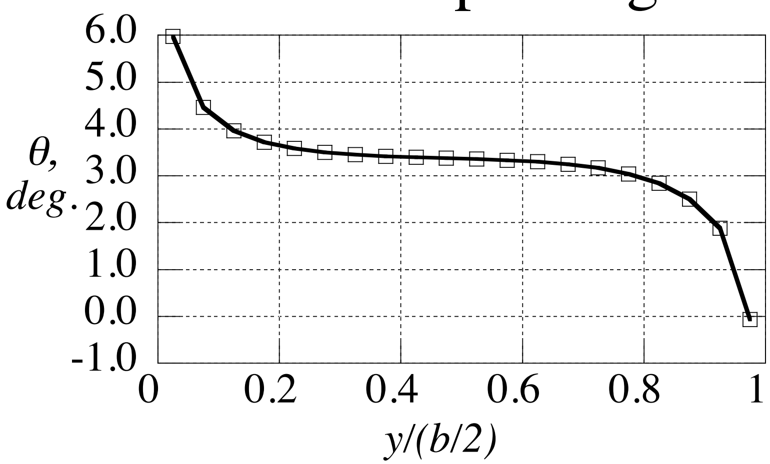
Without twist and camber: don't get full effect of sweep

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

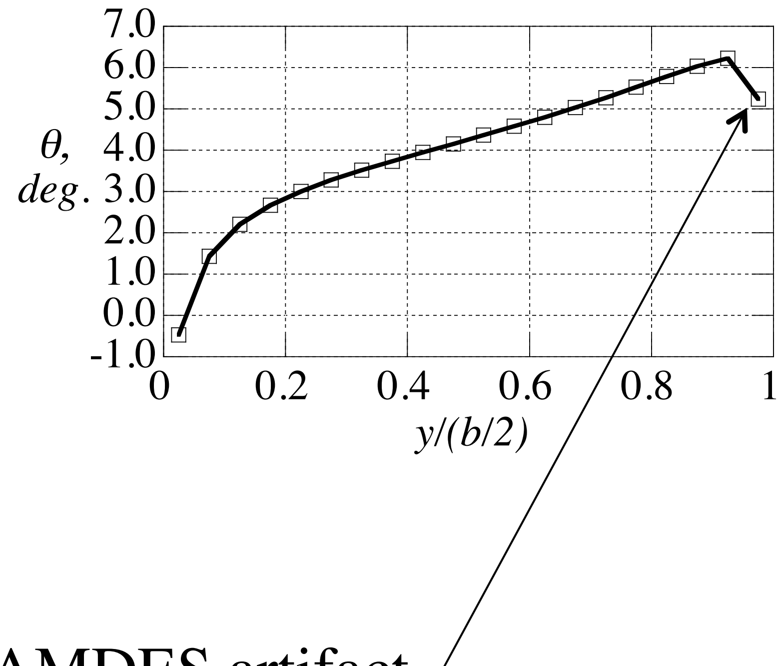
Now: Design
Typical Twist Distributions
- to improve isobars/spanloads -

from LAMDES on the software website

Aft Swept Wing

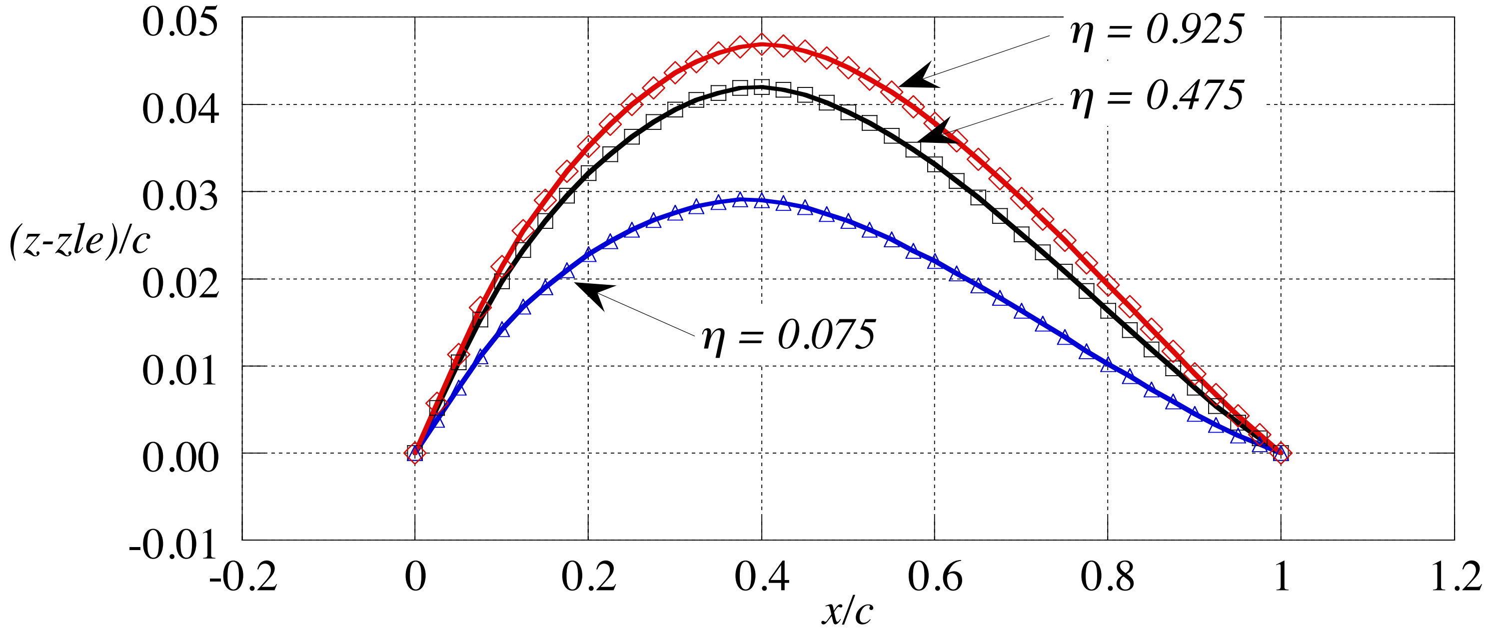


Forward Swept Wing



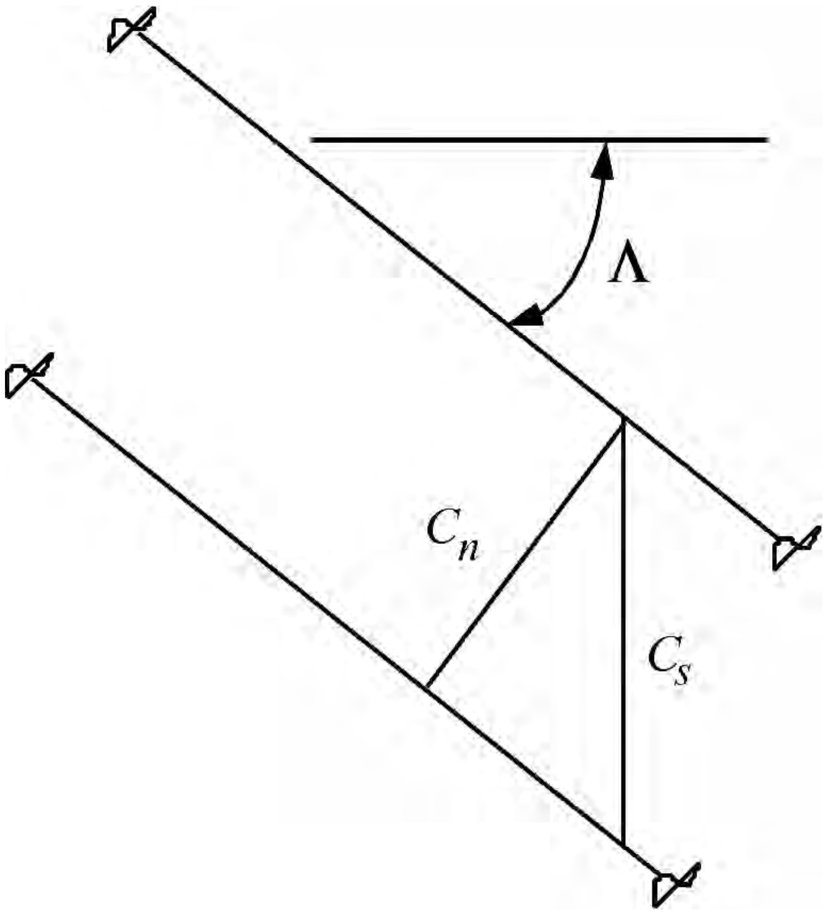
A LAMDES artifact

Design
Typical Camber Variation



Cambers from the LAMDES code on the software website

Relating 2D and 3D



$$c_{2D} = c_s \cos\Lambda$$

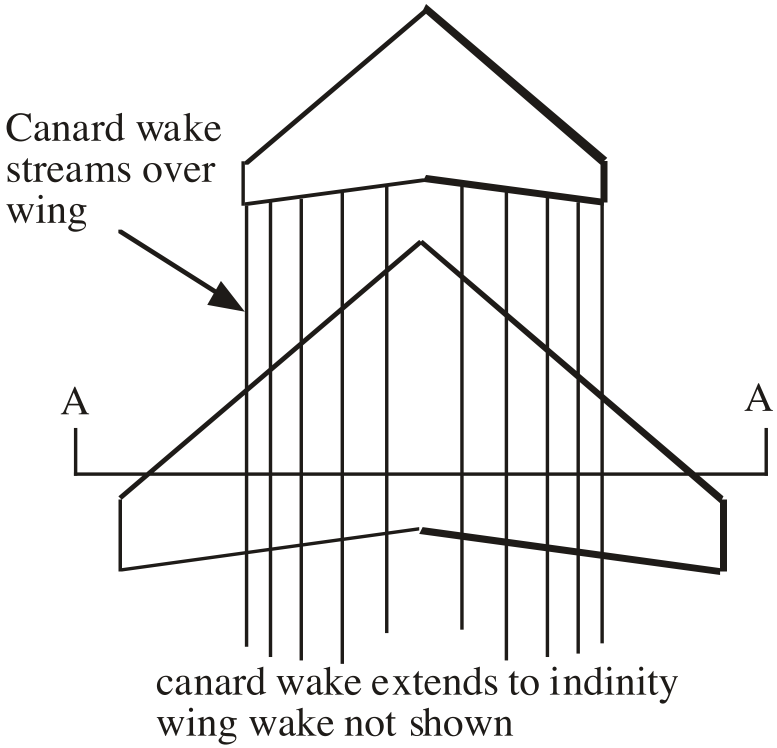
$$M_{2D} = M_\infty \cos\Lambda$$

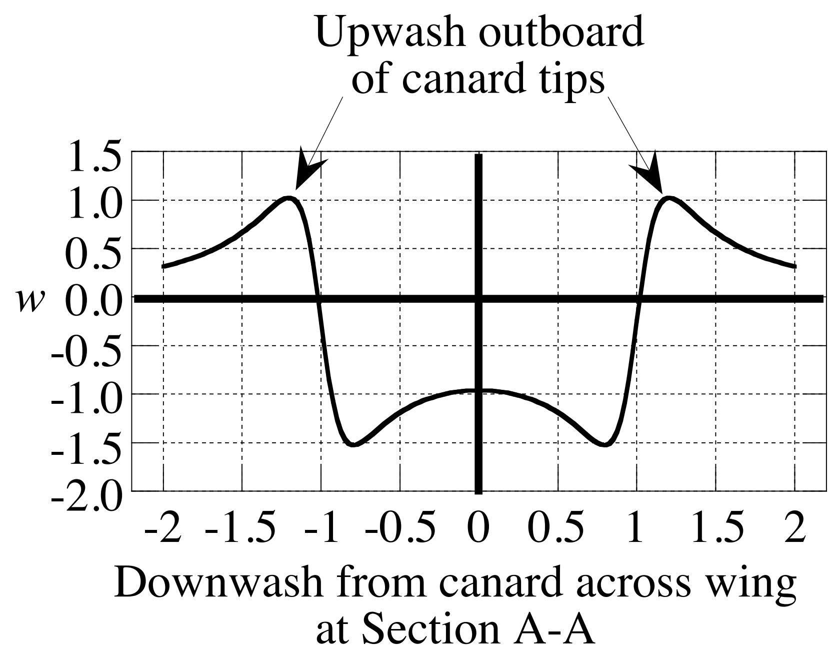
$$t/c)_{2D} = t/c)_s / \cos\Lambda$$

$$c_{L_{2D}} = c_{L_n} / \cos^2\Lambda$$

The airfoil problem is converted to 2D (normal), solved (designed), and put in the wing 3D

Now Canards
Canard-Wing Interaction

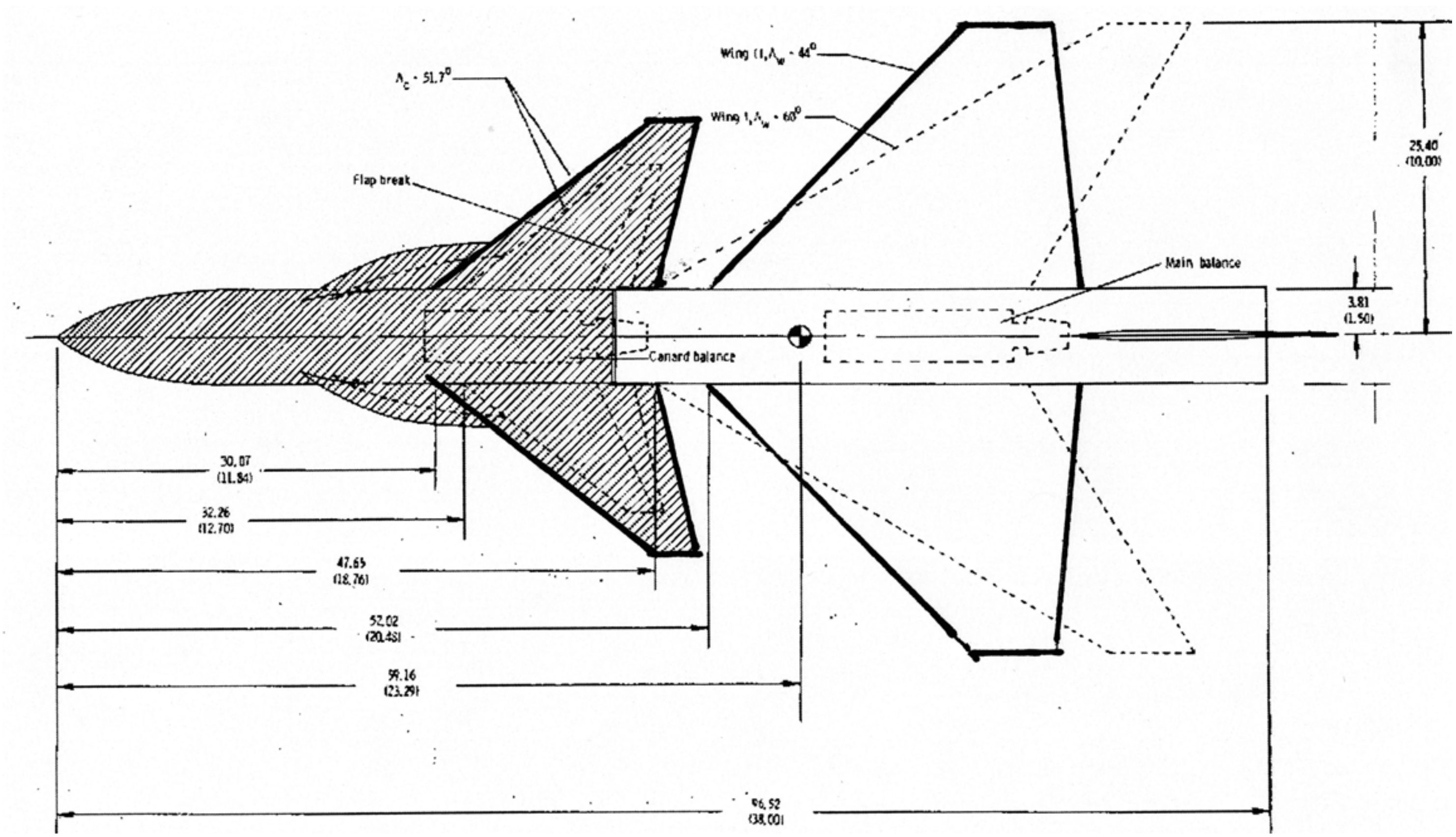




Look at example from WT testing

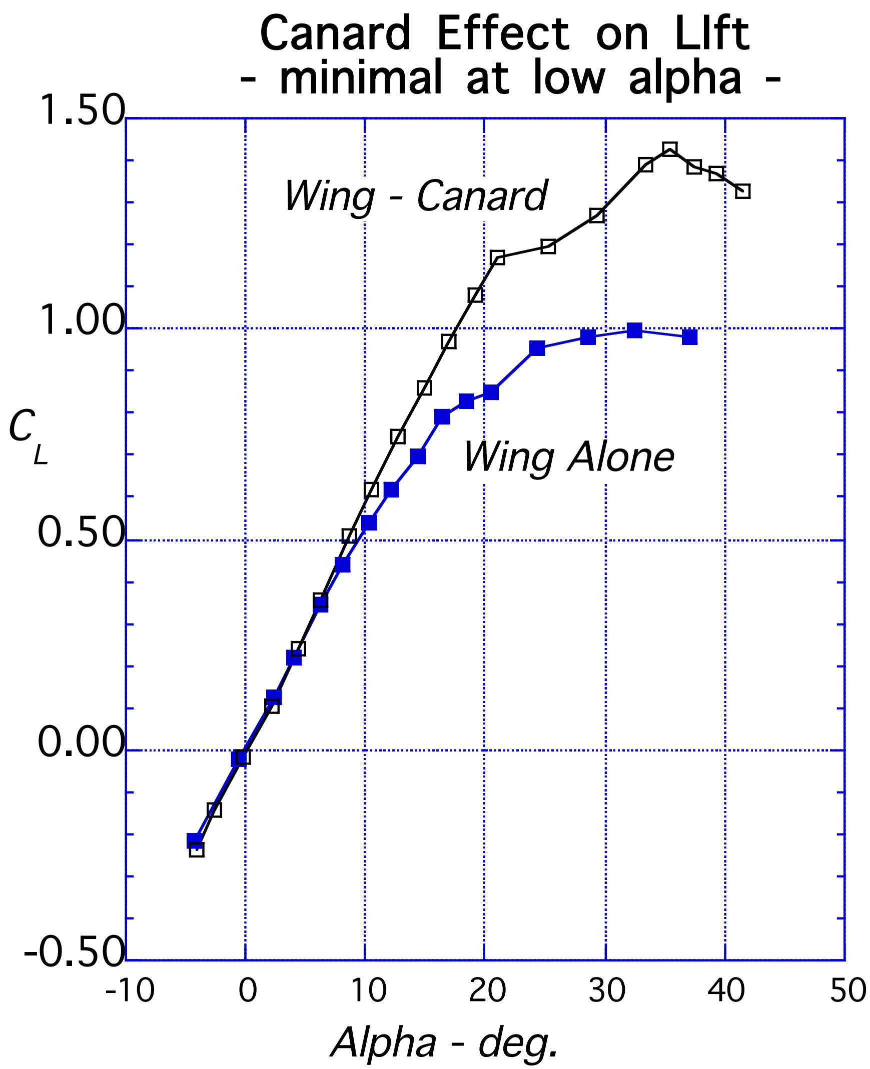
Wing tested at NASA Langley, NASA TN D-7910 by Blair Gloss

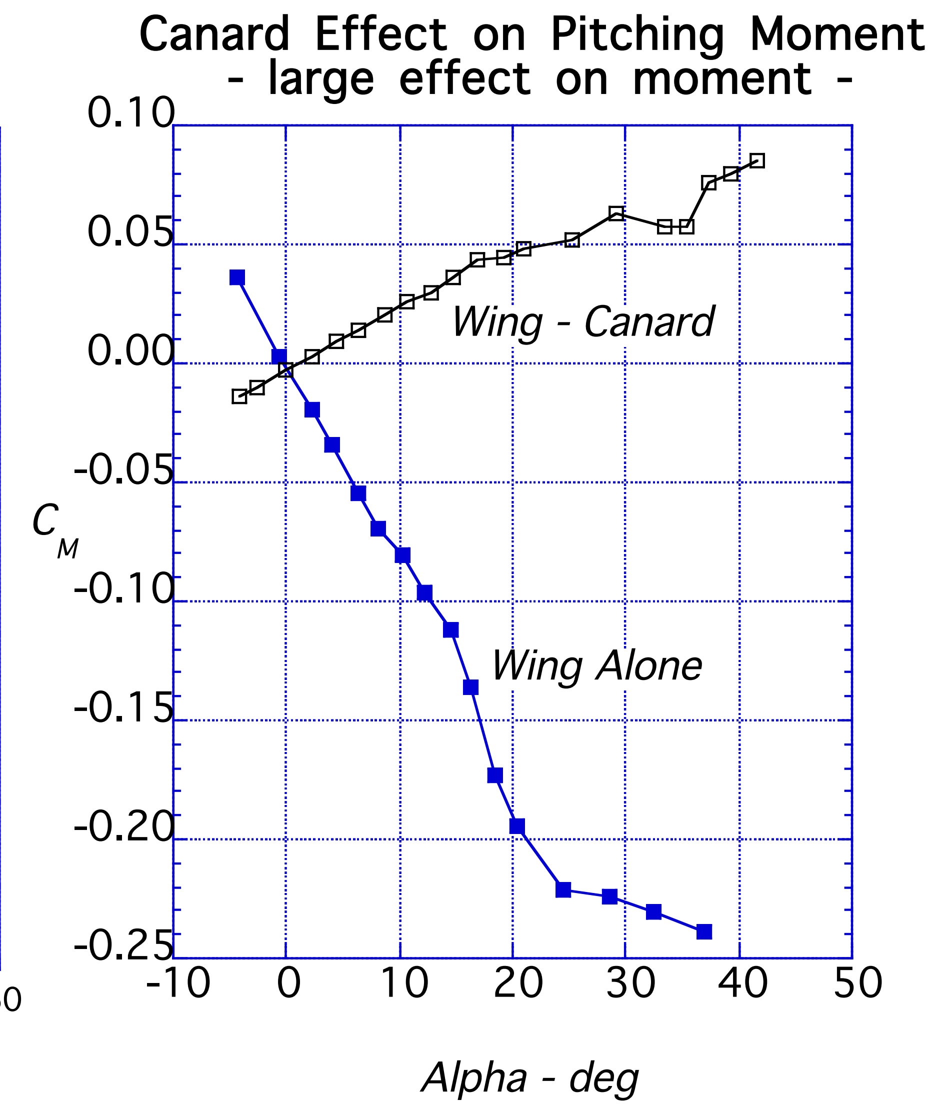
Several combinations tested, we illustrate the outlined wing and canard



Note: all the test results are tabulated in the NASA TN

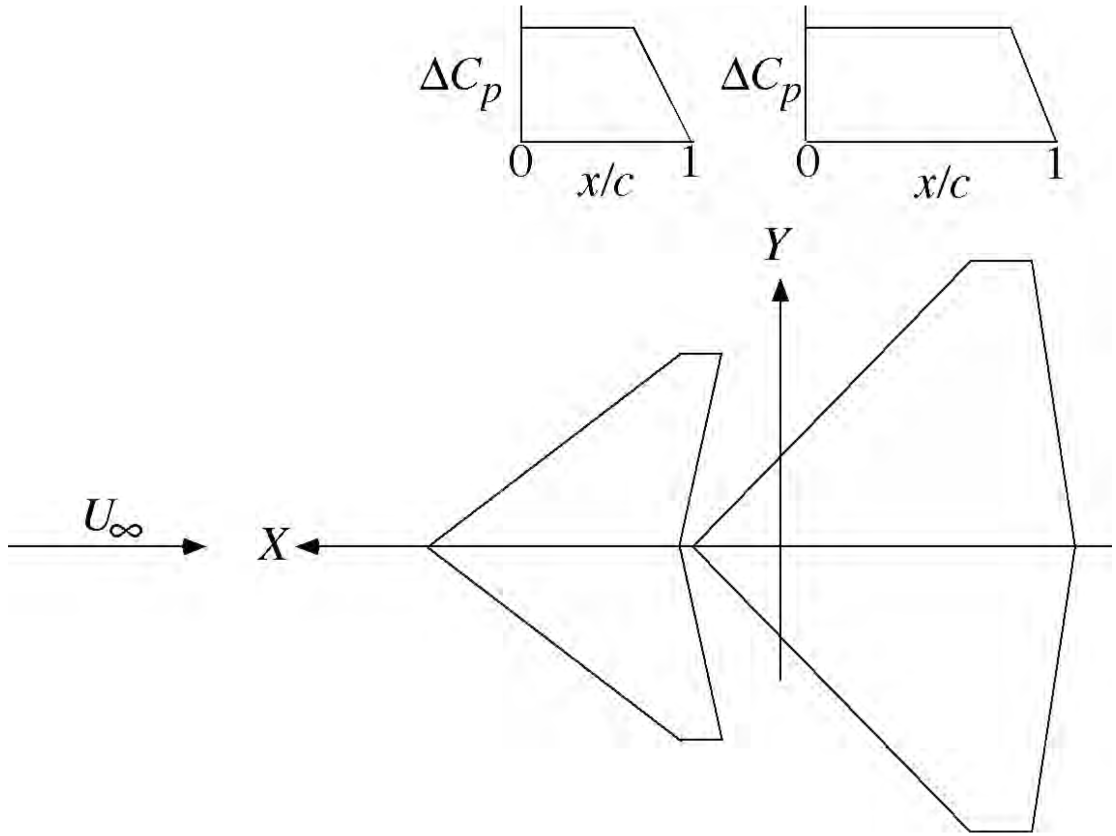
Canard Effects on Lift and Moment





NASA TN D-7910 by Blair Gloss

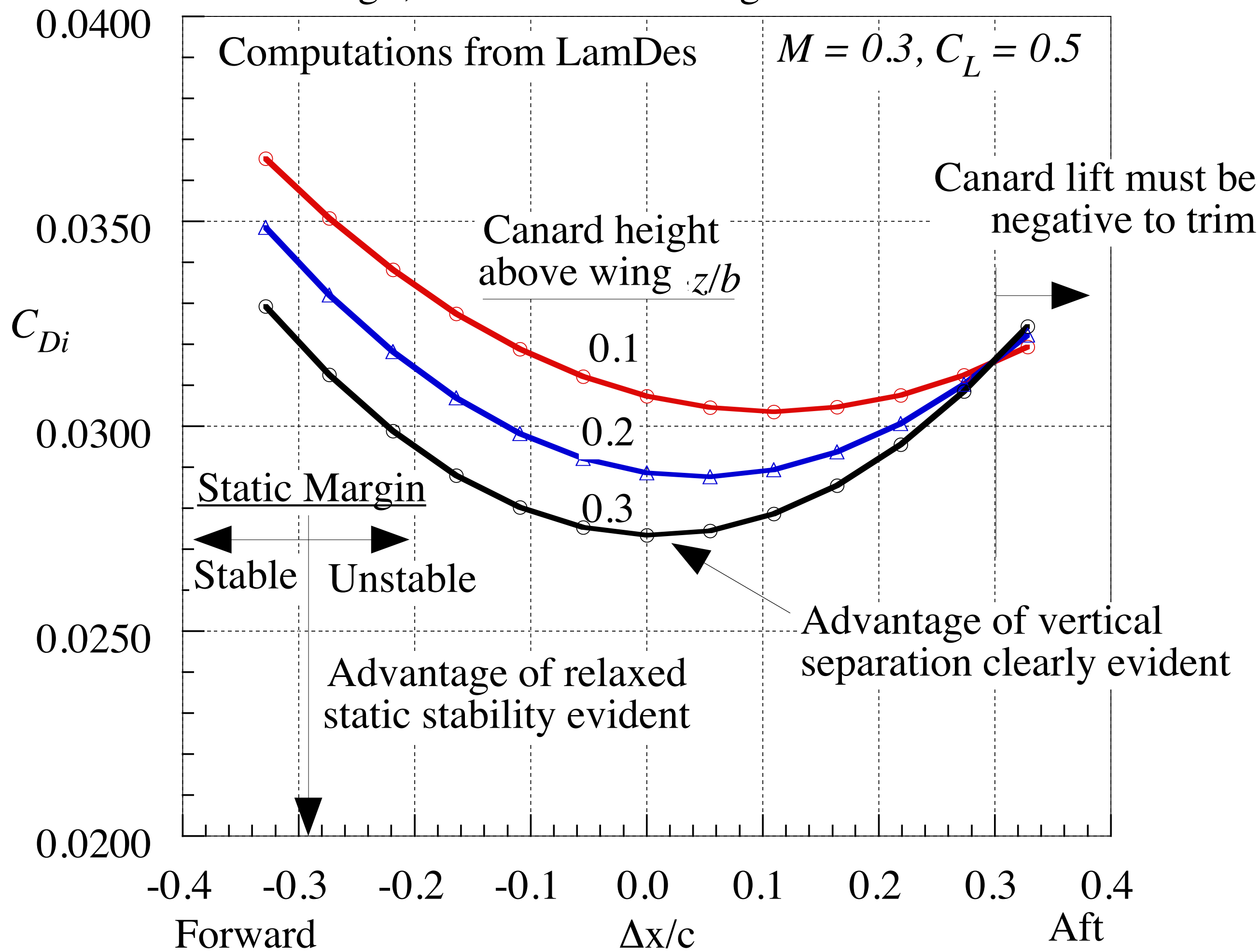
Example for Minimum Induced Drag Calculations



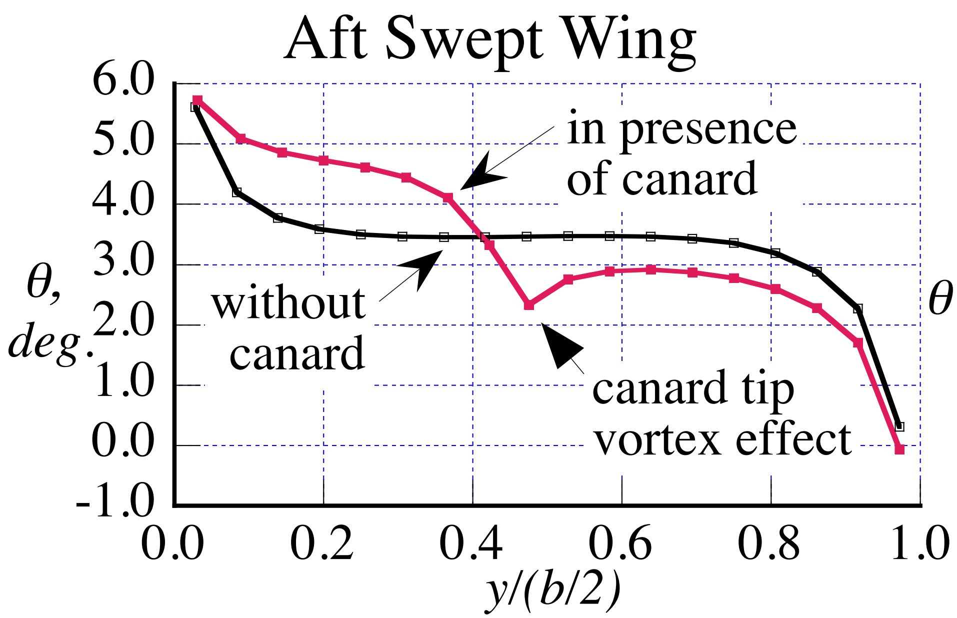
Sample case in John Lamar's NASA TN with LAMDES

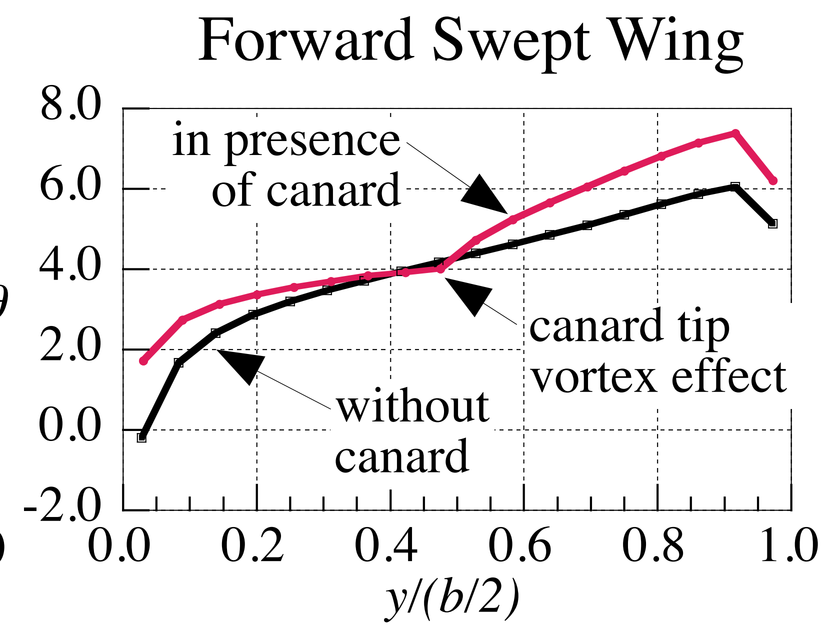
Canard Wing Induced Drag

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



Typical Required Twist Distribution

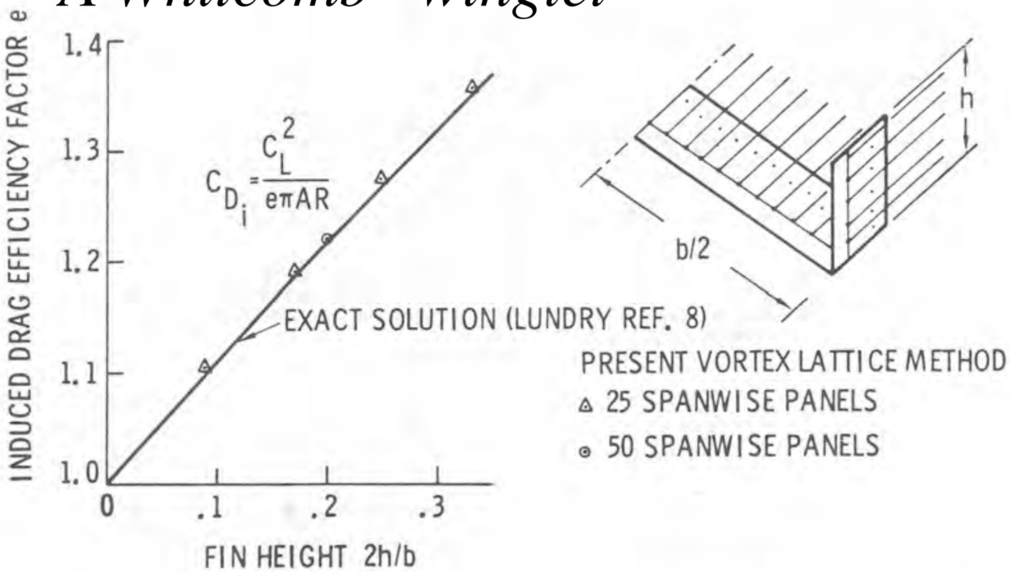




Actual twist values are heavily dependent on the canard load!

Some Variations: Tip treatment

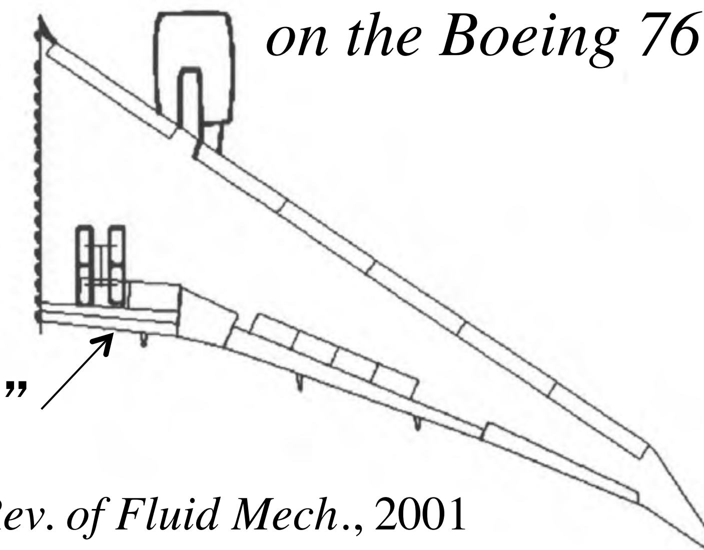
A Whitcomb "winglet"



from Feifel, in NASA SP-405, 1976

Rounding the intersection leads to a "blended winglet"

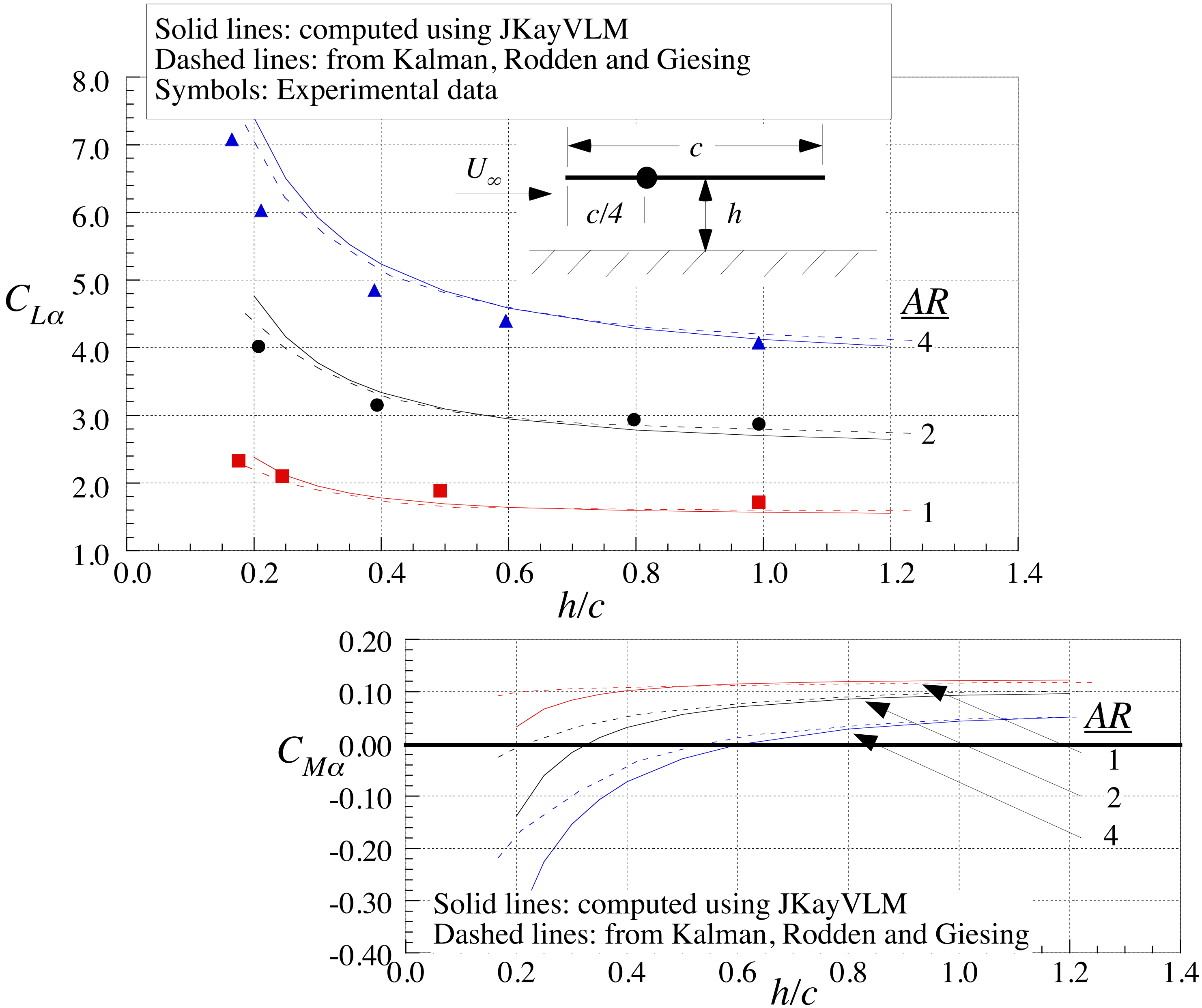
The "Raked Wingtip" used on the Boeing 767-400



Note "Yehudi"

from Kroo, *Ann. Rev. of Fluid Mech.*, 2001

Ground Effects from VLM



But ground effect can be complicated

A G650 crashed in New Mexico, April 2, 2011 – both pilots died
Why? C_{Lmax} **IGE can be less than** C_{Lmax} **OGE with flaps down**

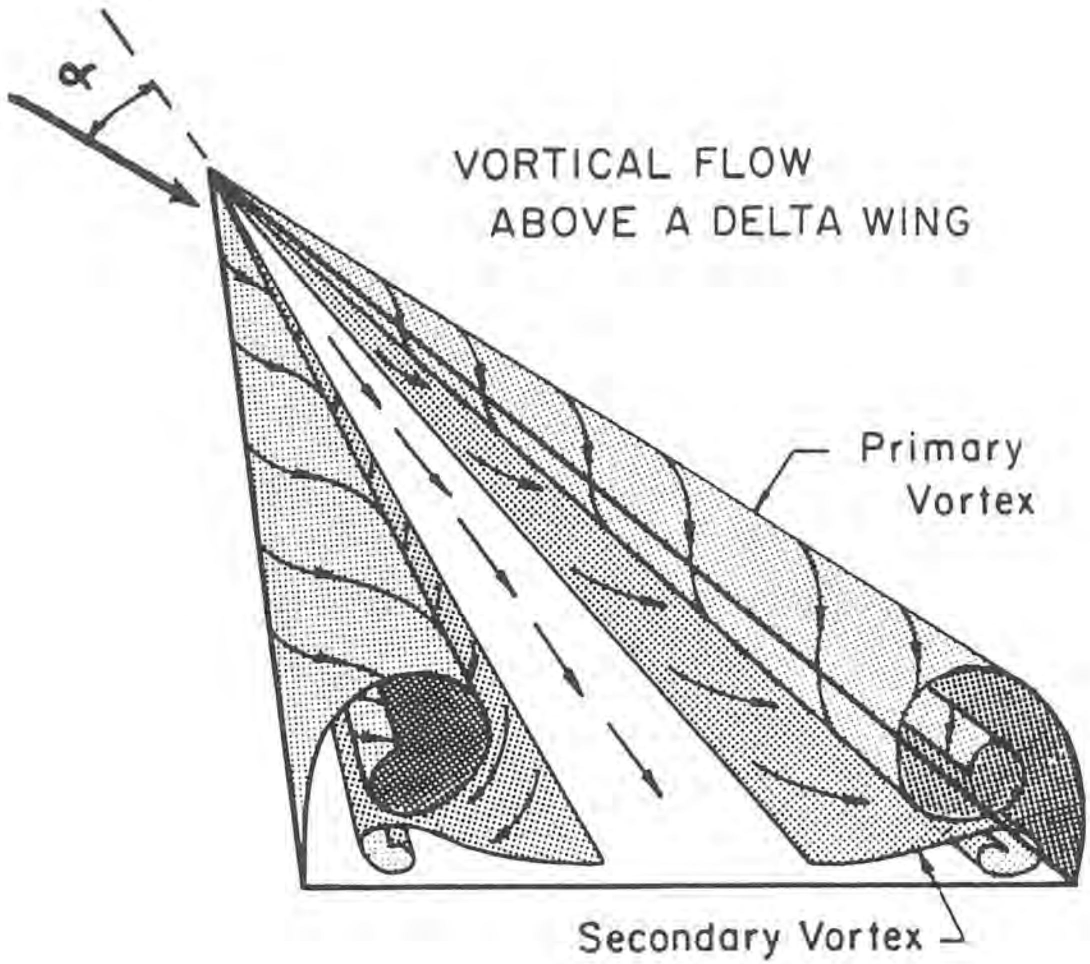
Data showed adverse flap effects *for* C_{Lmax}, NACA TN 705, 1939

IGE:
In Ground Effect

OGE:
Out of Ground Effect

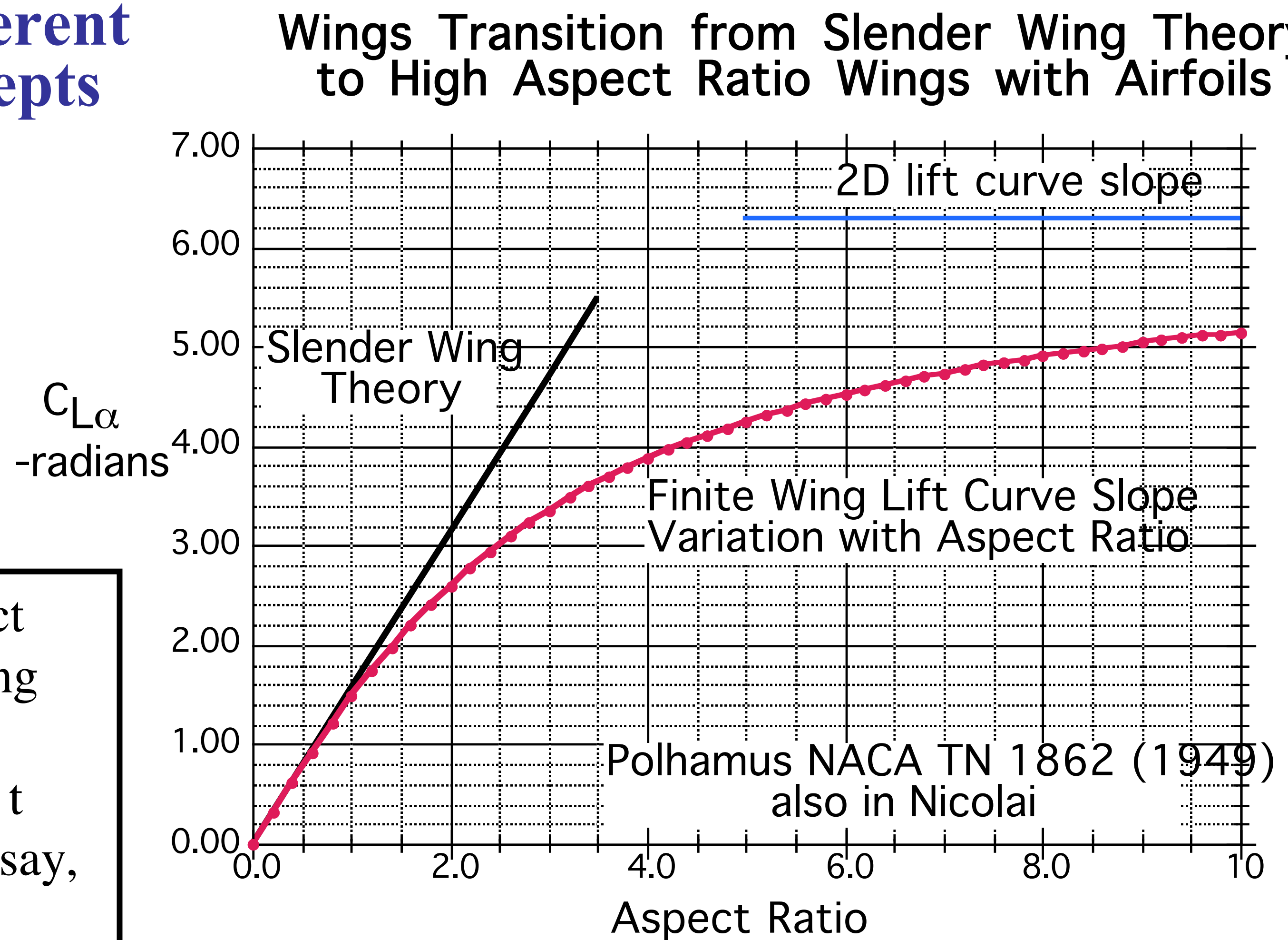
A completely new category

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.

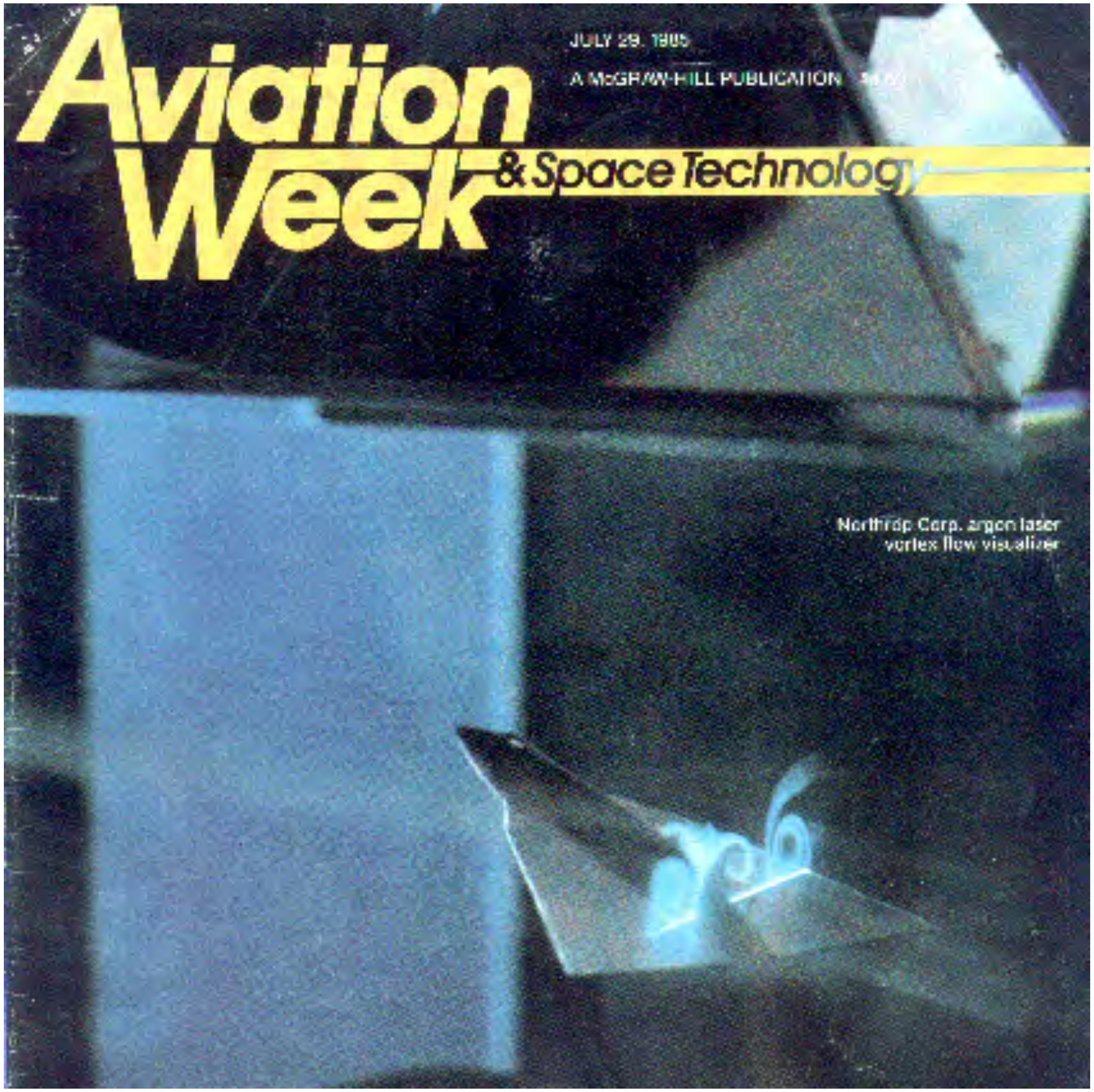
High aspect ratio wings approach the 2π slope
The slender wing slope is $(\pi/2)AR$

Laser Light Sheet Leading Edge Vortex Flow

Light Sheet is a great way to see the LE vortex

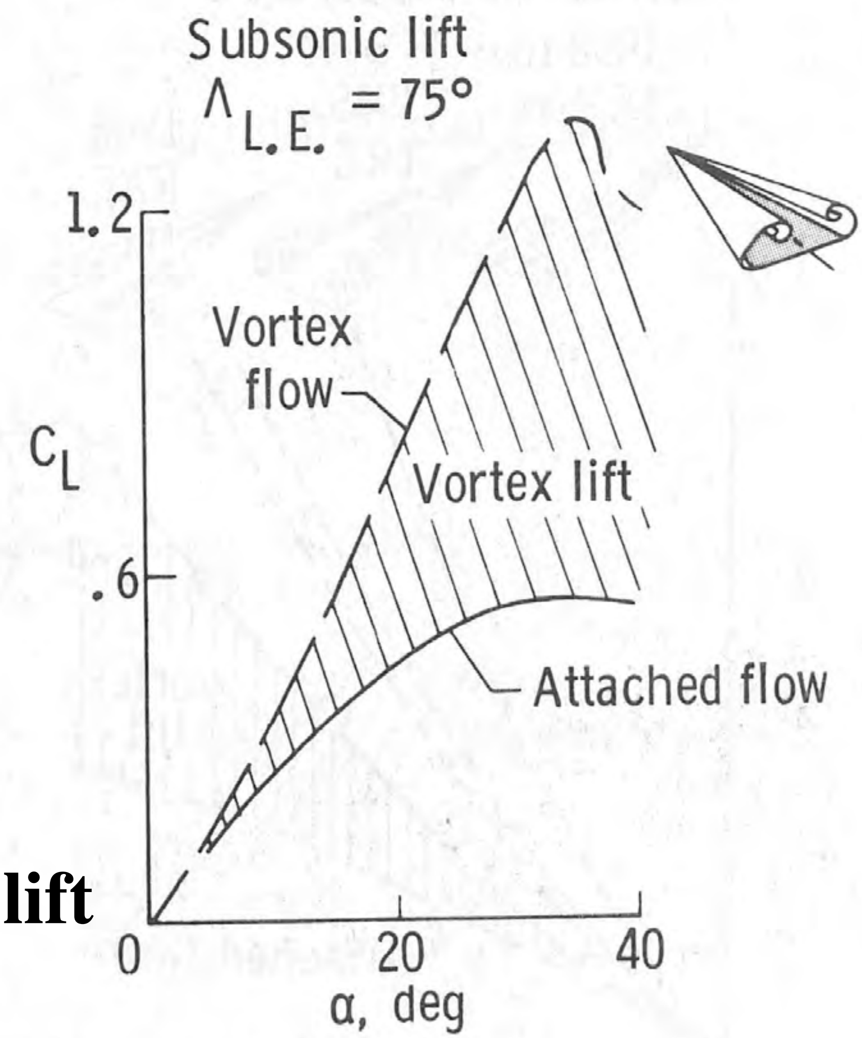
Northrop IR & D example of flow over a delta wing configuration.

Exhibited at the 36th Paris air show.



Aviation Week & Space Technology, July 29, 1985

Vortex Lift

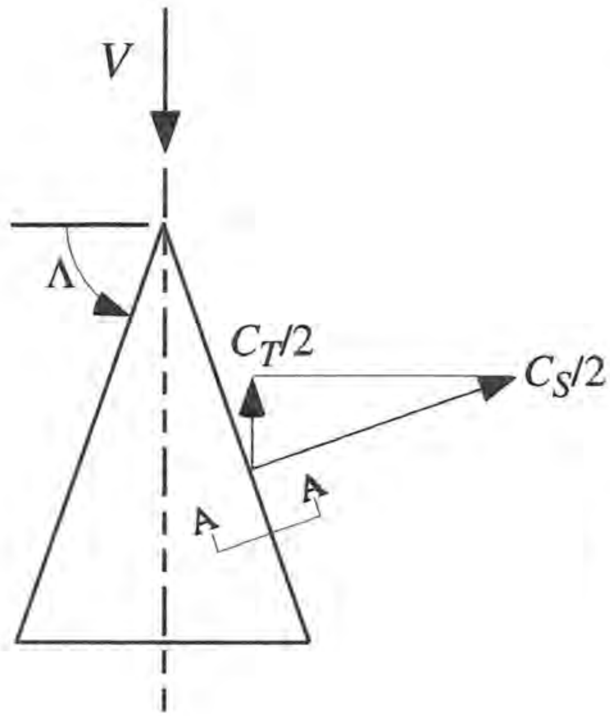


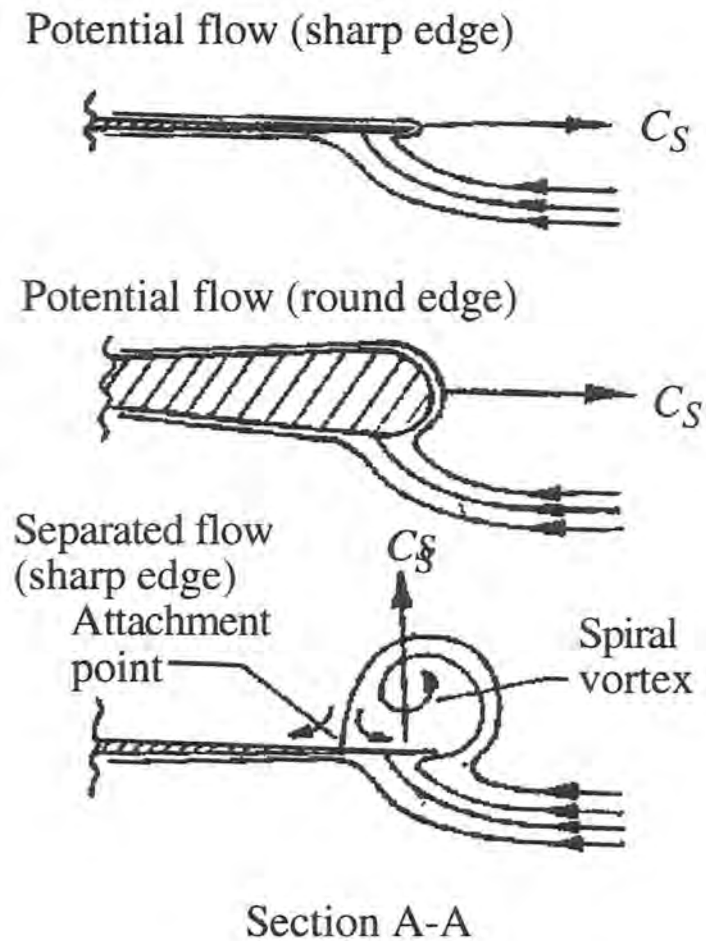
Drawback?
It's "draggy" lift

Thanks to James Stewart you can see a video of the flowfield:

https://www.youtube.com/watch?v=5_jt4x_TpOI

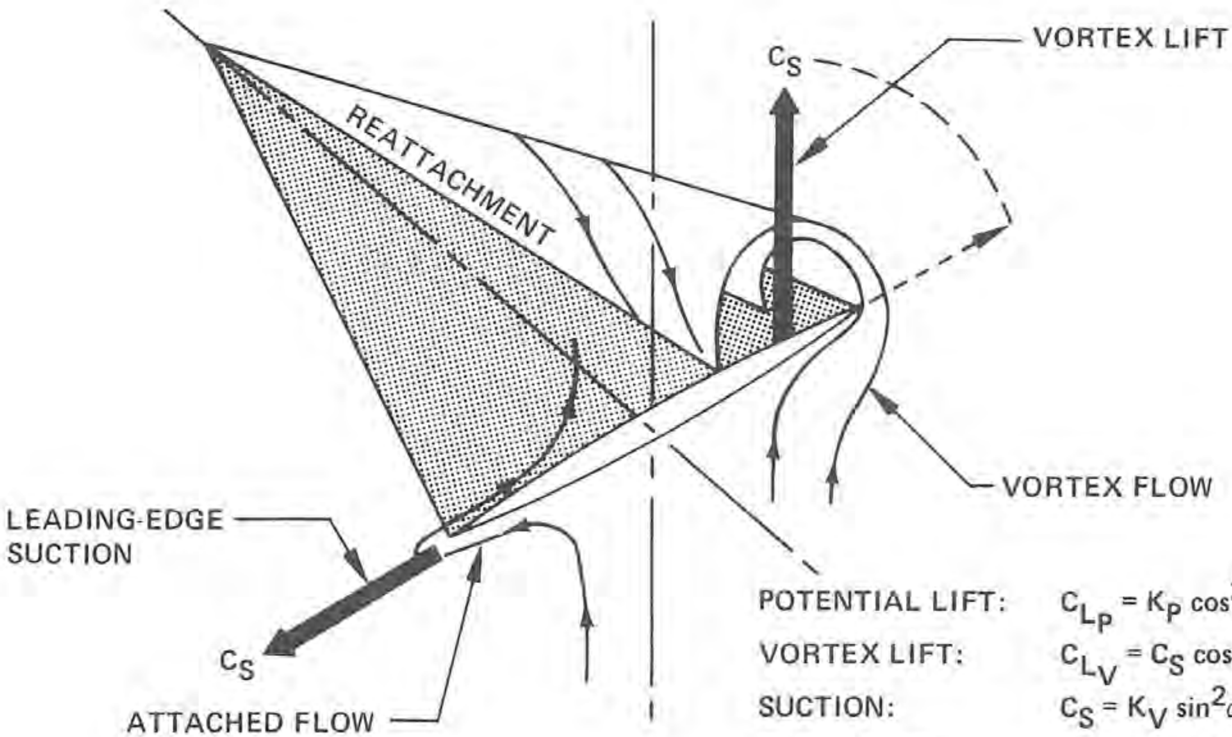
The Polhamus LE Suction Analogy





Edward C. Polhamus,
NASA TN D-3767

Another View of the Suction Analogy



POTENTIAL LIFT: $C_{L_P} = K_P \cos^2\alpha \sin\alpha$

VORTEX LIFT: $C_{L_V} = C_S \cos\alpha$

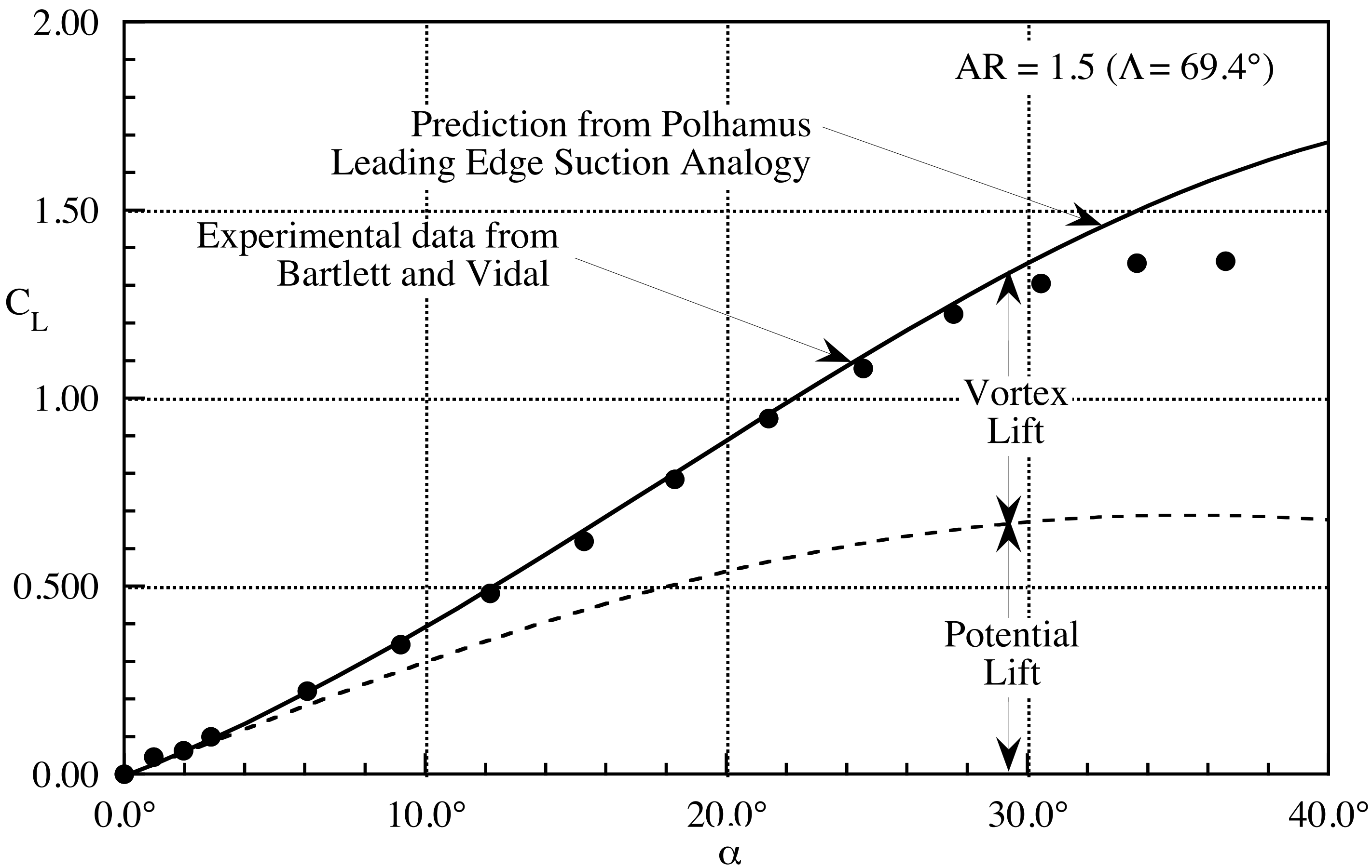
SUCTION: $C_S = K_V \sin^2\alpha$

TOTAL LIFT: $C_{L_T} = K_P \cos^2\alpha \sin\alpha + K_V \cos\alpha \sin^2\alpha$

DRAG DUE TO LIFT: $\Delta C_D = C_{L_T} \tan\alpha$

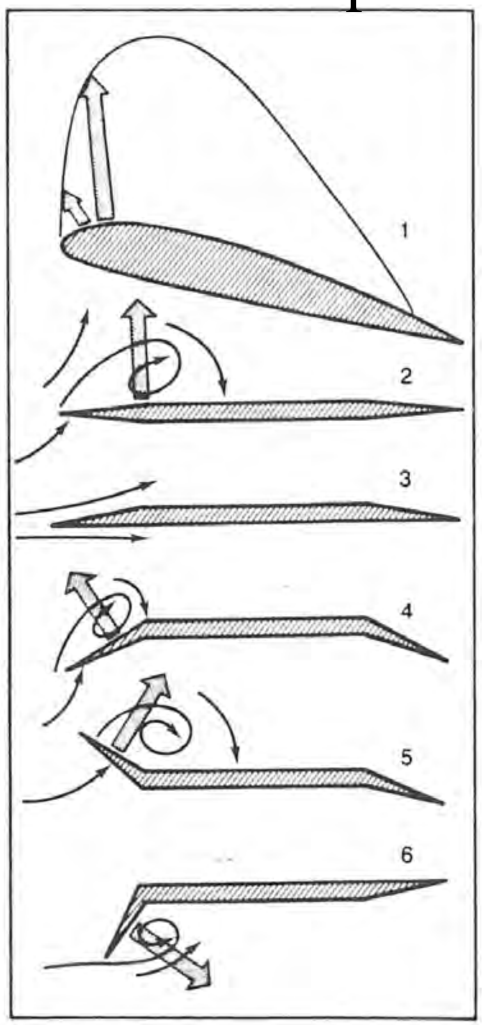
R.M. Kulfan, Wing Geometry Effects on Leading Edge Vortices, AIAA 79-1872

Results of the Polhamus Suction Analogy



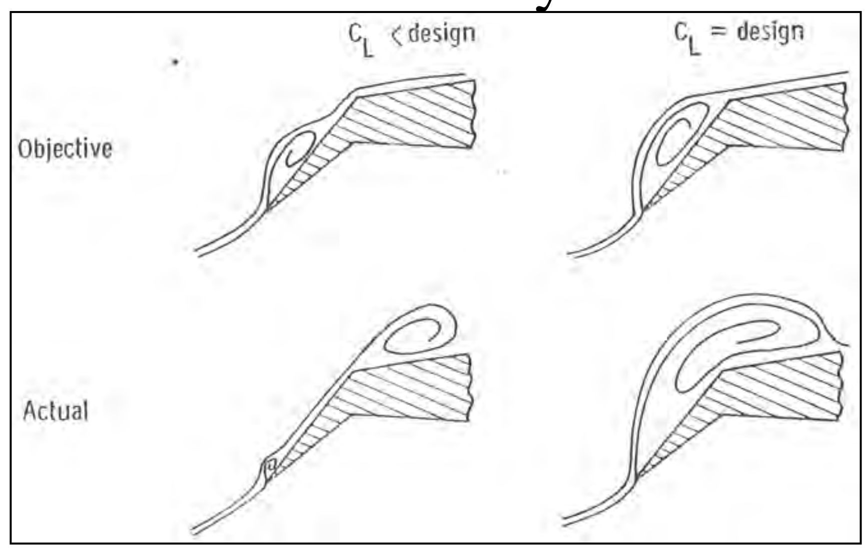
Reduce Drag with a *Vortex Flap*?

The Concept



Flight International, 16 March 1985

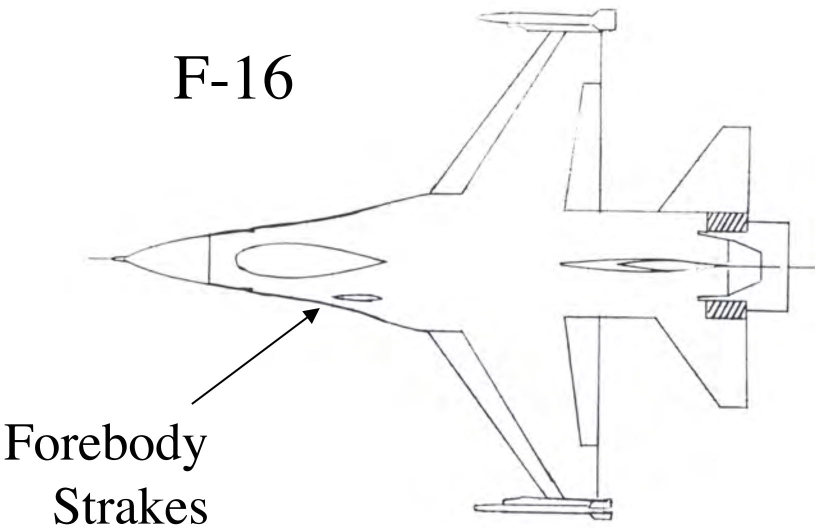
The reality?

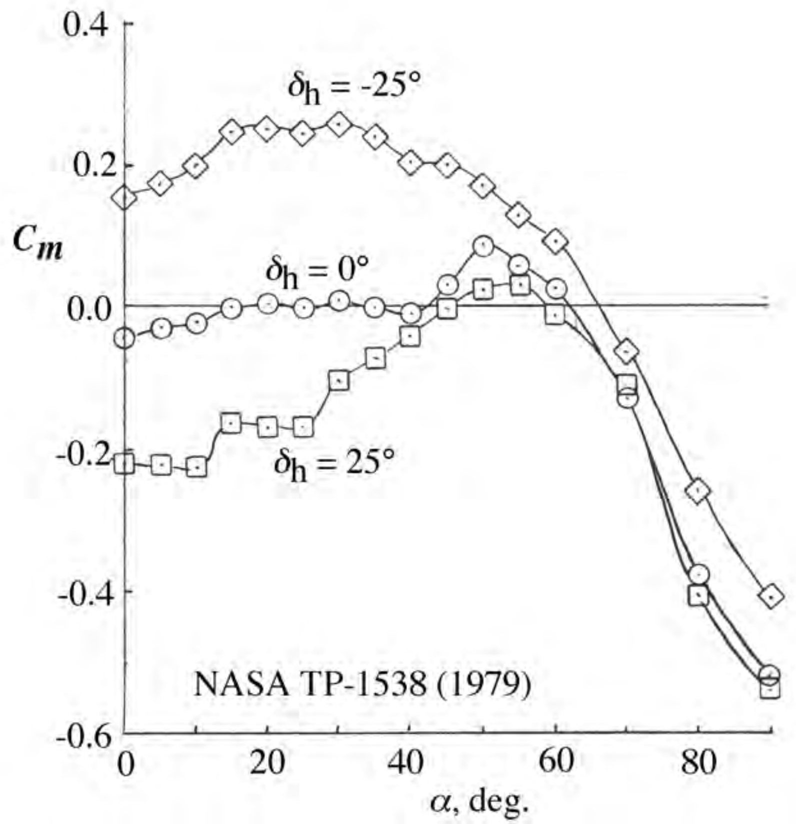


This concept was briefly popular, but it proved too hard to achieve.

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

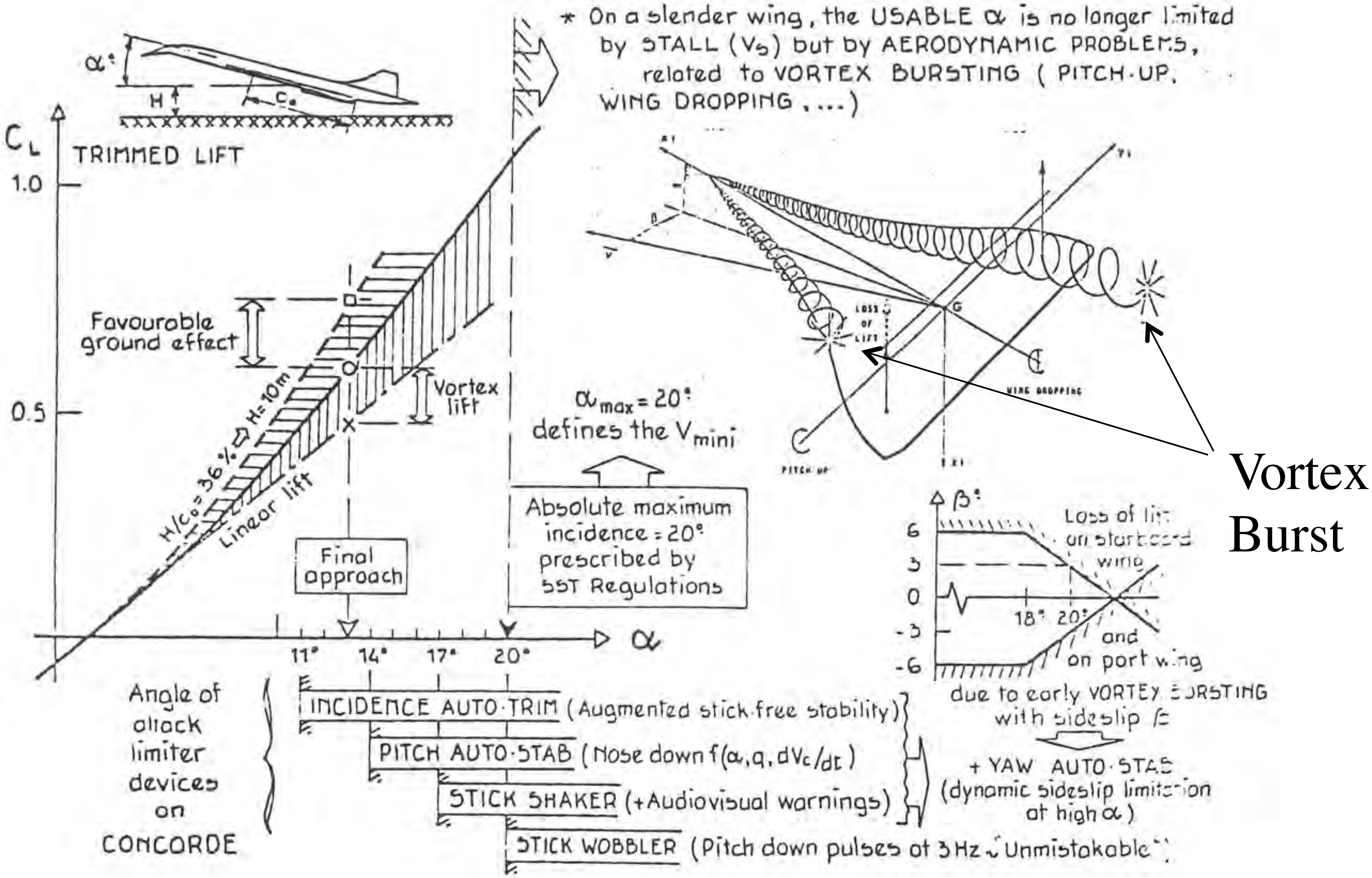




Note: you can apply the LE Suction Analogy to the strake in VLMpc

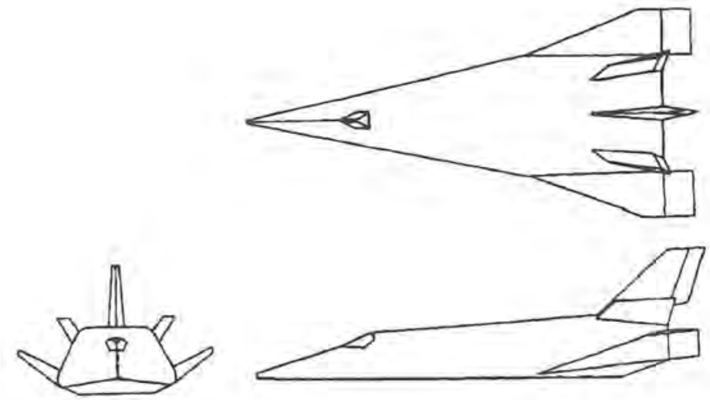
Note: Eventually the horizontal tail size was increased 25%

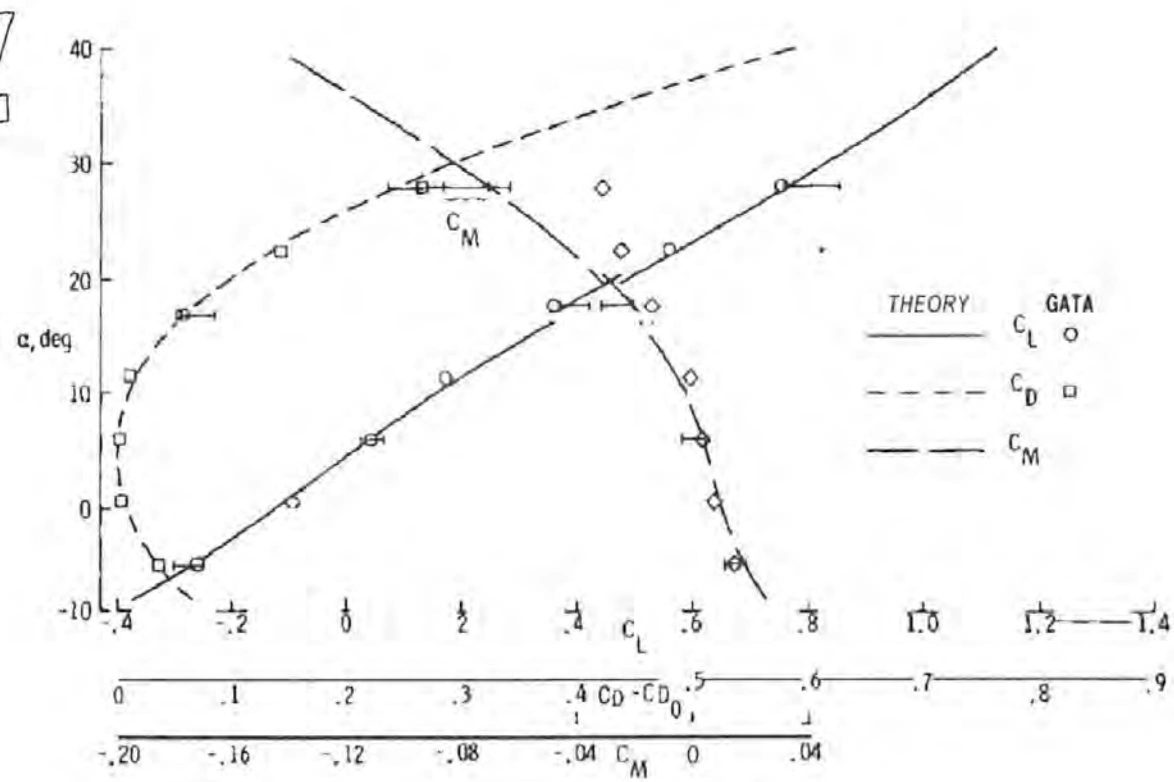
The Concorde Exploited Both Ground Effects and Vortex Lift to be Even Somewhat Practical



From Poisson-Quinton, Sustained Supersonic Cruise Aircraft Experience

And VLM works for Hypersonic Class Concepts





Jimmy Pittman and James Dillon, "Vortex Lattice Prediction of Subsonic Aerodynamics of Hypersonic Vehicle Concepts," *Journal of Aircraft*, October 1977, pp. 1017-1018.

To Conclude

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