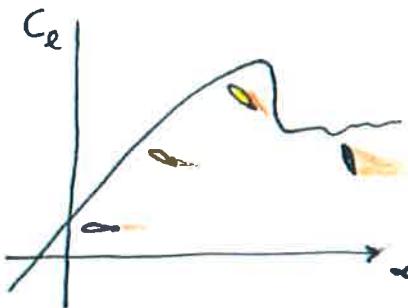


Lesson 26

High Lift

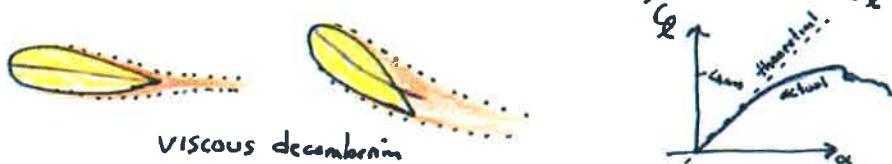
Read: A.O. Smith's "High Lift Aerodynamics" Paper

High Lift combines many of the concepts that we have discussed. What is common among all high lift applications? Separation.



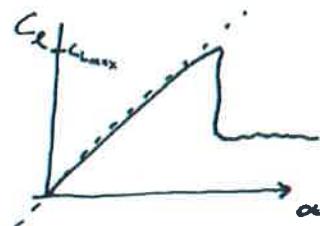
The art of high lift is the art of delaying, mitigating or eliminating separation while maximizing circulation.

When studying the BL topics, we briefly saw how a thickening BL affects C_L .



We can call the point when viscous decambering leads to reduced C_L from the max C_L as trailing edge stall

Stall also has another dominant mode, the leading edge stall where the separation begins at the LE. This mode is typically sharper and of more magnitude. (and more unstable).

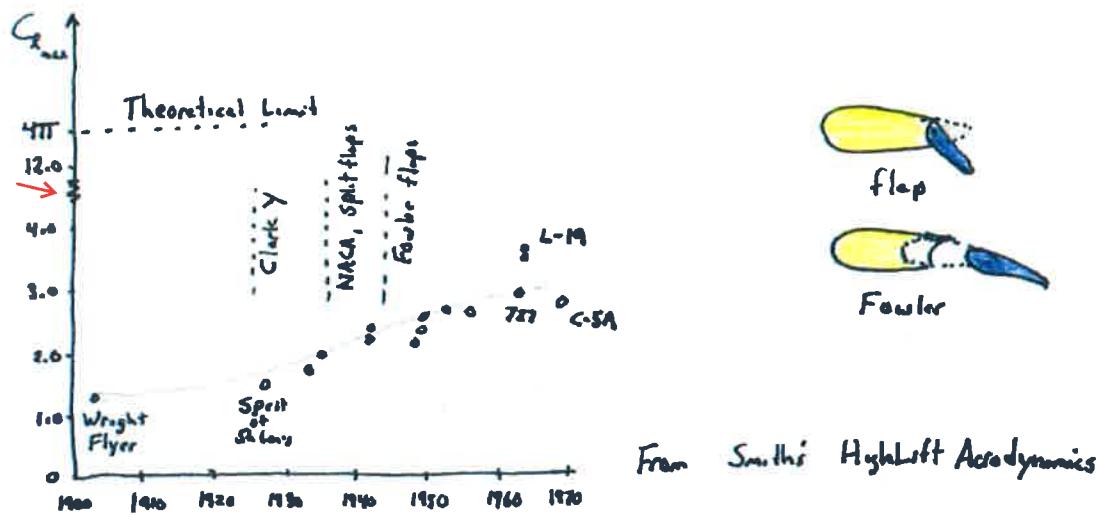


Why would we choose an airfoil with this abrupt stall behavior? Performance

Both TE and LE stall can occur,

The Piper PA38 Tomahawk was designed for spin training and uses the sharper GAW 1 airfoil. tiny.cc/PA38Stall

What are the limits of $C_{L\max}$?



Where does the theoretical limit come from?

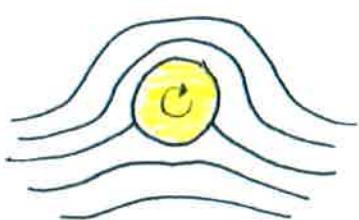
- Passive surface, no active suction or blowing
- Incompressible Inviscid flow over a circle



$C_L = 0$



$C_L > 0$



$$V_\theta = \underbrace{-U \left(1 + \frac{R^2}{r^2}\right) \sin\theta}_{\text{doublet}} + \underbrace{\frac{\Gamma}{2\pi r}}_{\text{vortex}}$$

$$\text{at } r=1 \text{ and } \theta=+90^\circ$$

$$V_\theta = -U (1+1) \sin 90^\circ + \frac{\Gamma}{2\pi r} = 0$$

$$\Gamma = 2\pi \cdot 2U$$

$$C_L = \frac{\Gamma}{8U} = \frac{\rho V \Gamma}{8U^2} = \frac{\rho V \cdot 4\pi U}{8\pi U^2} = \boxed{4\pi}$$

$C_{L\max} \sim 12.5$



Multielements (slats, slots, flaps)

Aileron, flaps shift αC_L , slats and slots shift $\alpha C_{L_{stab}}$

Auto-slats on commercial aircraft mitigate stall (tiny.cc/AutoSlitTestFlight)

Fowler flaps also increase wing area.

Slot combination	$C_{L_{max}}$	$C_{D_{min}}$	$\frac{C_{L_{max}}}{C_{D_{min}}}$	$\alpha_{C_{L_{max}}}$ degrees
	1.291	0.0152	85.0	15
	1.772	0.0240	73.8	24
	1.596	0.0199	80.3	21
	1.548	0.0188	82.3	19
	1.440	0.0164	87.8	17
	1.902	0.0278	68.3	24
	1.881	0.0270	69.7	24
	1.813	0.0243	74.6	23
	1.930	0.0340	56.8	25
	1.885	0.0319	59.2	24
	1.885	0.0363	51.9	25
	1.850	0.0298	62.1	24
	1.692	0.0228	74.2	22
	1.672	0.0214	78.2	22
	1.510	0.0208	72.6	19
	1.662	0.0258	64.4	22

(a) Multiple fixed slots.

FIG. 134. Aerodynamic characteristics of a Clark Y wing with slots and flaps.

Slot combination	$C_{L_{\max}}$	$C_{D_{\min}}^*$	$\frac{C_{L_{\max}}}{C_{D_{\min}}}$	$\alpha_{C_{L_{\max}}}^*$ degrees
	1.950	0.0152	128.2	12
	2.182	0.0240	91.0	19
	2.235	0.0278	80.3	20
	2.200	0.0340	64.7	21
	2.210	0.0270	81.8	20
	1.980	0.0164	120.5	12
	1.770	0.0164	108.0	14
	2.442	0.0208	117.5	16
	2.500	0.0258	96.8	18
	2.185	0.0214	102.0	18
	2.261	0.0243	93.2	19
	2.320	0.0319	72.7	20
	2.535	0.0363	69.8	20
	2.600	0.0298	87.3	20
	2.035	0.0298	68.3	21

* $C_{D_{\min}}$ with flap neutral.

(b) Multiple fixed slots and a slotted flap deflected 45 degrees.

FIG. 134. (Concluded)

Wing Stall

Demonstration: tiny.cc / Stall VGS

$$60 \text{ kts} \rightarrow 45 \text{ kts}$$

$$W = L = \frac{1}{2} \rho V_0^2 C_{L_{max}} = \frac{1}{2} \rho V_{Vg}^2 C'_{L_{max,Vg}}$$

$$\begin{aligned} C'_{L_{max,Vg}} &= \frac{V_0^2}{V_{Vg}^2} C_{L_{max}} = \frac{60^2}{45^2} C_{L_{max}} \\ &\approx 1.78 C_{L_{max}} \end{aligned}$$

Clean	clean	1:00	60 kts
TO flaps	140	60 kts	58 kts
Full flaps	210		
VGS outer	245		
clean	335		
flaps	415		
100 VGS	800		

Adding VGS improved $C_{L_{max}}$ by 78%!

Early NACA flow visualization (1938)

tiny.cc / Airfoil CLNACA

Planes, Clouds, and Vortices

tiny.cc / Planes Clouds Vortex

Watch ground effect and vortex density variations at 4:00 !!

Prop vortex cores at 5:13 (but only on the upper surface!) (especially at 4:15)

Compressible Limits.

$$\text{Given } C_p = \frac{P - P_\infty}{\frac{1}{2} \gamma M_\infty^2 P_\infty}$$

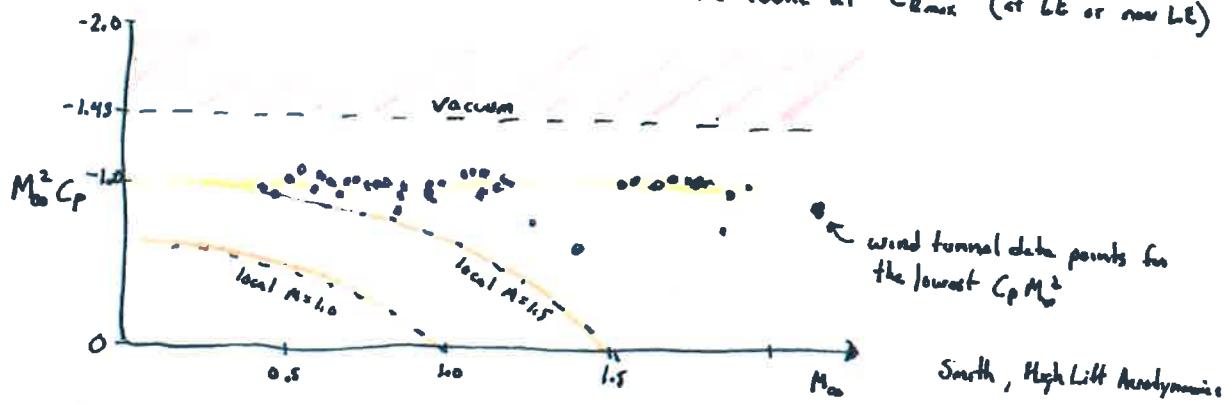
$$C_p = \frac{P - P_\infty}{\frac{1}{2} \gamma M_\infty^2 P_\infty}$$

$$\text{For a vacuum, } p=0 \Rightarrow C_p = \frac{-P_\infty}{\frac{1}{2} \gamma M_\infty^2 P_\infty} = \frac{-2}{\gamma M_\infty^2}$$

$$\text{Or, } M_\infty^2 C_p = -\frac{2}{\gamma} \approx -1.43 \text{ for air} \quad (\text{typo in ADTA p. 308})$$

This is how XFOIL provides a limit for C_p (---) when specifying a Mach #
dashed lines

From many experiments, the following pressure coefficients are found at C_{max} (at LE or near LE)



Mayer found an almost universal limit to $M_\infty^2 C_p$ of 1.0 or 70% of vacuum.

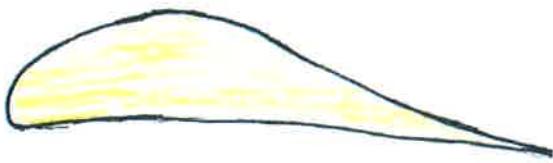
You can estimate C_{max} from inviscid tools (for LE shell)

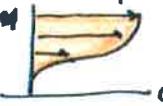
See Valarezo and Chin, Method for the Prediction of Wing Maximum Lift
 J. Aircraft V31 N.1 1994

Paper suggests $C_{peak} - C_{TE} \lesssim 14$ and dependent on Re when $Re < 10^{10}$
 or so.

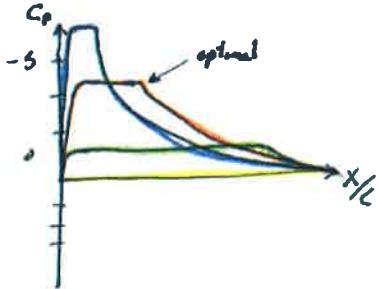
Useful for correcting LSWT subscale C_{max} results to full scale.

Liebeck Family of flow separation optimized airfoils.



Recall the discussion of incipient separation in Falkner Skan flows. The boundary layer profile is self similar . Liebeck through a crafty insight created a high performance and high lift airfoil section. Two characteristics define this family.

- 1) Rapid LE acceleration up to a rooftop C_p value
- 2) Pressure recovery to the TE such that incipient separation is maintained from the rooftop to the TE.



But, the question remains, which rooftop Mach # should be picked for max C_{max} ?

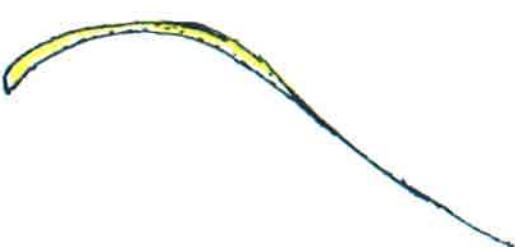
In other words, which has the most area under the curve?

The upper surface $C_{max,upper} = 2.03$ for laminar flow rooftop

$C_{max,upper} = 1.0$ for turbulent flow rooftop.

- - - - -
- laminar flow helps
- lift is this application
- But, not always in
- other applications

The bottom surface can also use inverse techniques to give $C_l = 3.06$ at $C_0 = 51$ counts



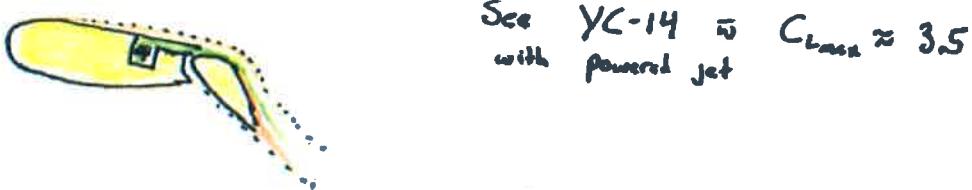
Suction, Blown Flaps, and Jets. (Active Flow Control)

Browse through Hoerner's Fluid Dynamic Lift for experimental results

Suction: Remove incipient separation by removing "bad" portion of BL.



Blown Flaps: Displace or remove defect in wake



Jets:

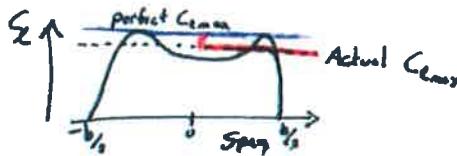


Practical considerations of $C_{L_{max}}$.

- Stall velocity scales with square root of $C_{L_{max}}$.

At some point, increasing S or active flow control is less trouble.

- As-built wings are never perfect. Left and Right panels will have slightly different $C_{L_{max}}$



e.g. Right stalls prior to left. Rolls right on stall.
pilot is grumpy....

- Active Flow Control increases drag weight.

- Reynolds' # dependent.

- Wind tunnel $C_{L_{max}}$ is conservative (almost always).

- Specialty airfoils for low Re are required (see: Selig 1223 or Eppler 423)

- Slat and Flap brackets and associated hardware must be considered.
 - weight
 - decreases $C_{L_{max}}$ over "clean" wing.

- 3D effects are important. $C_{L_{max}} \neq C_{L_{max}}$

- Non linear behavior

The flow preserves history. Thus $C_L \neq C_L(\alpha)$ but $C_L = C_L(\alpha, \dot{\alpha}, \ddot{\alpha}, \dots)$

